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SPECIAL INSTRUCTION SHEET

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2. ☒ Analysis — Check all that apply

Type of Analysis	☒ Engineering ☐ Performance Assessment ☐ Scientific
Intended Use of Analysis	☐ Input to Calculation ☒ Input to another Analysis or Model ☐ Input to Technical Document ☐ Input to other Technical Products

Describe use:

Provides input to the repository subsurface design with respect to the thermal environment in a lower temperature repository design.

3. ☐ Model — Check all that apply

Type of Model	☐ Conceptual Model ☐ Abstraction ☐ Mathematical Model ☐ System Model ☐ Process Model
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9. Checker	David Tang	David Tang	7/24/01
10. Lead/Supervisor	Alan Krug	Alan D. Krug	7/24/01
11. Responsible Manager	Robert Boutin	RSS Robert Boutin	7/24/01

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
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ACRONYMS

ANSYS	A computer program developed by ANSYS, Inc.
ASME	American Society of Mechanical Engineers
BSC	Bechtel SAIC Company
BWR	Boiling Water Reactor
CRWMS M&O	Civilian Radioactive Waste Management System Management and Operation Contractor
CSNF	Commercial Spent Nuclear Fuel
DHLW	Defense High Level Waste
DIRS	Document Input Reference System
DOE	Department of Energy
DS	Drift Spacing
DTN	Data Tracking Number
FV	Forced Ventilation
GJ	gigajoule
LL	Initial linear heat load
MGR	Mined Geologic Repository
NV	Natural Ventilation
pk	package
PWR	Pressurized Water-Reactor
QARD	Quality Assurance Requirements and Description
SGI	Silicon Graphics
SR	Site Recommendation
TBV	To Be Verified
TDMS	Technical Data Management System
WP	Waste Package
°C	degree Celsius
2D	Two-dimensional
3D	Three-dimensional
J/kg·K	Joules per kilogram-Kelvin
K	Kelvin
kg	kilogram
kg/m·s	kilograms per meter-second
kW	Kilowatt
mm	millimeter
m	meter
m^3	cubic meter
s	second
sec	second
W/m·K	Watt per meter-Kelvin

1. PURPOSE

1.1 PURPOSE

As indicated in the *Technical Work Plan for Subsurface Design Section FY 01 Work Activities*, the repository subsurface design for this analysis will be based on the lower temperature operations mode (CRWMS M&O 2001a, p. 6 of 30). This analysis will provide input for intended use in the *Technical Work Plan* task, *Overall SR Subsurface Layout Analysis*, which is tasked to develop and describe the overall subsurface layout, including performance confirmation facilities, for the Site Recommendation (SR) design and incorporate current program directives for thermal management and SR design (CRWMS M&O 2001a, p. 14 of 30).

1.2 SCOPE

This analysis will show a base case repository, that will have a higher temperature operating mode at 1.45 kW/m [(1)], as the reference scenario. The analysis will show the thermal impact of a lower temperature operating mode repository with a thermal load of 1.0 kW/m [(2)] and perform a sensitivity analysis on possible variations to the lower temperature operating mode. The results will be based on the emplacement drift thermal load, emplacement drift spacing, forced air ventilation duration and the natural ventilation duration. The effect of the ventilation airflow rate and the duration that the ventilation will be maintained is considered as well. The case studies in this analysis are derived from the possible lower temperature operating modes presented in the *Lower-Temperature Subsurface Layout and Ventilation Concepts* (BSC 2001e, Section 6.1, pp. 40 of 126 and 41 of 126). The focus of this analysis will be on the primary block design inventory emplaced at a representative stratigraphic location. A qualitative determination of the lower block waste emplacement inventory thermal affect to the PTn and the zeolite layer is also discussed.

The output of this analysis is intended for use in the *Technical Work Plan* task *Overall SR Subsurface Layout Analysis* and it will serve as a vehicle to develop and perform the thermal analysis for the specific case studies of the lower temperature operating mode repository. The output will include the peak temperature values for the waste package surface, the emplacement drift wall, and the important geologic formations (PTn and zeolite layers) for each of the case studies to explore the lower temperature operating mode. This analysis will also provide the peak temperatures of the waste package surface, the emplacement drift wall and the air temperature for various lengths of emplacement drift. This analysis will show the impact of different thermal conductivity values used for the Tptpll geologic formation, and examine the sensitivity of predicted temperatures to the discretized drift segement size in the ventilation model. The models are conducted as two-dimensional (2D) abstractions of the potential thermal environment within the repository. A parametric study for a unique sample case consisting of a simple, three-waste package system is performed as a three-dimensional (3D) model as well. The scope for the 3D model is to show the axial temperature variation generated by a simple three-waste-package system.

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1 Higher temperature repository initial linear thermal load at emplacement, used throughout

2 Lower temperature repository initial linear thermal load at emplacement, used throughout

2. QUALITY ASSURANCE

As documented in the *Technical Work Plan for Subsurface Design Section FY 01 Work Activities* (CRWMS M&O 2001a, pp. A16 and A17), in accordance with AP-2.21Q Rev. 01, ICN 0, *Quality Determination and Planning for Scientific, Engineering, and Regulatory Compliance Activities*, it has been determined that the requirements of *Quality Assurance Requirements and Description* (QARD) (DOE 2000) are applicable.

The *Technical Work Plan for Subsurface Design Section FY 01 Work Activities* (CRWMS M&O 2001a, p. 19 of 30) does not specifically identify the method used to control the electronic management of data, per AP-SV.1Q, *Control of the Electronic Management of Data,* for ANSYS input/output for the SSF LT Facilities System with respect to the Thermal Management Analysis (CRWMS M&O 2001a, p. A16 of A31); however, the procedure to control the electronic management of data for the SSF LT Ground Control (CRWMS M&O 2001a, p. 19 of 30) is inferred to be applicable.

The thermal load does impact the performance of permanent items such as *Natural Barriers Important to Waste Isolation,* Paintbrush Nonwelded (PTn) Hydrologic Unit as documented in the *Q-List* (YMP 2001a, Appendix B, Section 1, p. B-2) which has the assignment "Item Important to Waste Isolation". However, thermal operating modes are not defined as an "Item Important to Waste Isolation".

This analysis was prepared in accordance with AP-3.10Q Rev. 02, ICN 4, *Analyses and Models.* Document inputs, references and unqualified data will be identified and tracked in accordance with AP-3.15Q Rev. 02, ICN 1, *Managing Technical Product Inputs*.

3. COMPUTER SOFTWARE AND MODEL USAGE

3.1 ANSYS COMPUTER SOFTWARE

A commercially available computer program, ANSYS Version 5.6.2 (CRWMS M&O 2001c, STN: 10145-5.6.2-00), was used to support the analysis. ANSYS is a general purpose, finite element analysis code, and is used in many disciplines of engineering, including structural, geotechnical, and mechanical, concerning thermal behavior of solids and fluids. The ANSYS Version 5.6.2 is installed on Silicon Graphics (SGI) workstation with the Unix operating system IRIX6.5 (CRWMS M&O CPU #114441 located in Las Vegas, Nevada). ANSYS Version 5.6.2 has been verified and validated using procedure AP-SI.1Q Rev. 02, ICN 04, *Software Management*. ANSYS Version 5.6.2 was used in thermal calculations for predicting the effect of waste emplacement. The input and output files for the ANSYS runs were archived and submitted to the Technical Data Management System (TDMS) and the Records Processing Center (DTN: MO0107MWDTEM05.011). A detailed discussion of the general features and fields of the application of the ANSYS code is presented in the User's Manual (SAS 1995).

The ANSYS Version 5.6.2 software was obtained from the Software Configuration Management in accordance with the AP-SI.1Q procedure. The software was appropriate for the applications used in this analysis. The software was used within the range of validation as specified in the software qualification report (CRWMS M&O 2001b, Section 7).

Use of the ANSYS software to perform scientific and engineering calculations and analyses has been widely accepted in the nuclear industry and other related engineering fields. The software was developed based on the following established mathematical and engineering theories and laws: Fourier's Law, Newton's Law of Cooling, and Stefan–Boltzmann Law. Selection of this software for the analysis indicates the adoption of these underlying scientific and engineering laws or models. Validation of these laws or models involves the examination of mathematical theories and the results of laboratory and field tests. The model validation also includes identification of scientific and engineering literature, parameter inputs, assumptions, initial and boundary conditions, and limitations. Since the ANSYS software has been validated and verified, in addition to the rigorous validation conducted by the software vendor before the release of the software, the underlying models are determined to be validated for use as long as the use is within the range of validation.

3.2 SPREADSHEET SOFTWARE

Microsoft Excel 97 spreadsheet software was used in calculating the heat generation rates used as inputs to the ANSYS models and the heat removal rates based on the energy balance to determine the exhaust air temperatures. It was also used to demonstrate some of the ANSYS results graphically. In the former application, simple arithmetic operations, such as addition, subtraction, multiplication, and division, were used. These calculations are presented in Attachments I through IX. In the latter application, the results from the ANSYS models were used as inputs, and the outputs are presented in the forms of figures in Attachments II through IX. User-defined formulas and/or algorithms are displayed where used. Microsoft Excel 97 is an exempted software product in accordance with AP-SI.1Q, Rev. 3, ICN 1, Section 2.1.1.

4. INPUTS

This section presents the inputs used in this analysis. This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the technical input information quality may be confirmed by review of the Document Input Reference System database.

4.1 DATA AND PARAMETERS

4.1.1 Stefan–Boltzmann Constant

The Stefan–Boltzmann constant value, 5.669×10^{-8} $W/m^2 \cdot K^4$ (Holman 1997, p. 396), is used for thermal radiation calculations.

4.1.2 Ventilation Air Properties

Ventilation air properties are listed in Table 4-1. These values are based on an intake air temperature of 25°C (298 K) and using linear interpolation from Holman (1997, p. 646). The air properties in Table 4-1 are not strongly pressure dependent, however air density is a function of the elevation. Therefore, the air density was assumed and was placed in Section 5.9.5

Table 4-1. Properties for Ventilation Air at 25°C (298 K)

Parameter	Value
Thermal Conductivity (W/m·K)	0.0261
Specific Heat (J/kg·K)	1,005.7
Dynamic Viscosity (kg/m·s)	1.8363×10^{-5}
Prandtl Number (dimensionless)	0.709

Sources: Holman 1997, p. 646.
Note: values are interpolated.

4.1.3 Titanium (Drip Shield) Properties

The thermal conductivity, thermal diffusivity, and specific heat of the titanium used for the drip shield are temperature dependent, and their values are given in Table 4-2 (ASME 1995, Table TCD, p. 611). The density used for titanium is 4,512 kg/m^3 (ASME 1995, Table NF-2, p. 620), and the emissivity is 0.63 (Lide 1995, p. 10-298).

Table 4-2. Thermal Properties of Titanium

Temperature		Thermal Conductivity		Thermal Diffusivity		Specific Heat
(°F)	(°C)[a]	(Btu/hr·ft·°F)	(W/m·K)[b]	(ft^2/hr)	(10^{-6} m^2/sec)[c]	(J/kg·K)[d]
70	21	12.68	21.946	0.359	9.264	525.00
100	38	12.52	21.669	0.352	9.084	528.68
150	66	12.25	21.201	0.340	8.774	535.54
200	93	12.00	20.769	0.331	8.542	538.87
250	121	11.85	20.509	0.322	8.310	547.01
300	149	11.72	20.284	0.314	8.103	554.79
350	177	11.60	20.076	0.306	7.897	563.47
400	204	11.45	19.817	0.300	7.742	567.31
450	232	11.35	19.644	0.294	7.587	573.83
500	260	11.29	19.540	0.290	7.484	578.67
550	288	11.23	19.436	0.286	7.381	583.64
600	316	11.20	19.384	0.283	7.303	588.25
650	343	11.17	19.332	0.280	7.226	592.96
700	371	11.15	19.298	0.278	7.174	596.16
750	399	11.18	19.350	0.276	7.123	602.10
800	427	11.20	19.384	0.275	7.097	605.37
850	454	11.23	19.436	0.274	7.071	609.20
900	482	11.30	19.557	0.273	7.045	615.25
950	510	11.36	19.661	0.272	7.019	620.79
1000	538	11.43	19.782	0.271	6.994	626.92
1050	566	11.51	19.921	0.270	6.968	633.64
1100	593	11.58	20.042	0.270	6.968	637.50

Source for Columns 1, 3, and 5: ASME 1995, Table TCD, p. 611

Note: a) °C=(°F-32)/1.8

b) Btu/hr·ft·°F=1.7307 W/m·K (Holman 1997, inside front cover)

c) ft^2/hr=25.8064×10^{-6} m^2/s

d) $\alpha=k/\rho c$ (Holman 1997, p. 5)

where α is thermal diffusivity, k is thermal conductivity, ρ is density (4,512 kg/m^3), and c is specific heat.

4.1.4 Rock Properties

The rock bulk density, thermal conductivity, and specific heat values are used in the ANSYS model of the repository thermal environment. For each of the rock stratigraphic units the values are listed in Table 4-3.

Table 4-3. Bulk Density and Thermal Properties by Stratigraphic Unit

T/M Unit	Stratigraphic Unit	Bulk Density (Kg/m^3)	Thermal Conductivity (W/m · K)		Specific Heat (J/kg · K)		
			T ≤ 100 °C	T > 100 °C	T < 95 °C	95 °C ≤ T ≤ 105 °C	T > 105 °C
TCw	Tpcpv3	1970	1.57	1.02	1097	10634	943
PTn	Tpcpv2	1460	1.10	0.80	1349	19414	1047
	Tpcpv1	1460	0.91	0.47	1349	19414	1047
	Tpbt4	1310	0.85	0.34	1320	18251	1047
	Tpy	1790	0.97	0.47	1128	11072	1047
	Tpbt3	1390	0.99	0.46	1291	17162	1047
	Tpp	1130	0.82	0.36	1291	17130	1047
	Tpbt2	1200	0.67	0.27	1288	17018	1047
	Tptrv3	1200	0.81	0.34	1288	17018	1047
	Tptrv2	1200	1.01	0.37	1288	17018	1047
TSw1	Tptrv1	2380	2.04	1.67	860	2422	943
	Tptrn	2150	1.61	1.17	797	4836	1013
	Tptrl	2130	1.68	1.31	979	6474	943
	Tptpul	2130	1.97	1.06	979	6474	943
TSw2	Tptpmn	2250	2.33	1.60	833	5360	1090
	Tptpll	2210	2.02 [a] 1.76 [a]	1.20 [a] 1.22 [a]	960	5812	943
	Tptpln	2270	1.86	1.42	948	5390	943
TSw3	Tptpv3	2270	2.10	1.75	883	2476	1047
CHn1	Tptpv2	1960	1.52	0.83	1066	8811	1047
	Tptpv1	1660	1.26	0.66	1296	17329	1047
	Tpbt1	1660	1.30	0.68	1003	6597	1047
	Calico[b]	1520	1.16	0.58	1319	17271	1041
CHn2	Tacbt	1790	1.31	0.69	1265	16166	1047

Source: Thermal Conductivity and Specific Heat from DTN: SN0011T0571897.014
Bulk Density from CRWMS M&O 2000d, Table 5, p. 12
[a] refer to Section 5.7.6
[b] average values used

4.2 CRITERIA

4.2.1 Maximum Allowable Zeolite and PTn Temperatures

The maximum allowable temperature of the zeolite layers located beneath the emplacement area horizon is < 90 °C (Curry 2001, Section 5.2.29, p. 5-12). The maximum allowable temperature at the base of the PTn stratigraphic unit is < 70 °C (Curry 2001, Section 5.2.30, p. 5-12).

4.2.2 End Points of the Thermal Range

The low end point of the thermal range is to maintain the waste package surface temperature below 85°C and the high end point of the thermal range is to control the rock temperatures so that there is free drainage between the emplacement drifts (Curry 2001, Section 5.1.1.3, p. 5-1).

4.2.3 Maximum Emplacement Drift Wall Temperature

The maximum emplacement drift wall temperature shall not exceed 96°C during normal preclosure operations, nor, at any position or anytime, exceed 200°C (Curry 2001, Section 5.2.24, p. 5-12).

4.2.4 Forced Ventilation Flow Rates

An air flow rate of 15 m^3/s is used for the forced ventilation during the repository preclosure period (CRWMS M&O 2000a, Section 2.3.2, p. 28 of 72).

4.2.5 Emplacement Drift Diameter and Spacing

The emplacement drifts have a diameter of 5.5 m and a center-to-center spacing of 81 m (CRWMS M&O 2000b, Section 1.2.1.3 and 1.2.1.5, p. 11 of 79).

4.2.6 Minimum Spacing Between Waste Packages

The minimum spacing between waste packages is 10 cm (CRWMS M&O 2000b, Section 1.2.1.4, p. 11 of 79).

4.2.7 Drip Shield Installation

The drip shield will be installed at the time of the repository closure (Curry 2001, Section 5.2.11, p. 5-11).

4.2.8 Ventilation System Operational Life

The operational life of the ventilation system will support the deferral of closure for up to 300 years (CRWMS M&O 2000a, Section 1.2.1.12, p. 10 of 72).

4.2.9 Emplacement Drift Split Length

A maximum emplacement drift split length of 600 meters is assumed (CRWMS M&O 2000b, Section 2.2.2.4, p. 23 of 79).

4.2.10 Soil Surface Temperature

The Mined Geologic Repository (MGR) shall limit the change in the temperature of the soil near the surface above the repository in accordance with the *Yucca Mountain Site Characterization Project Requirements Document* (Curry 2001, Section 5.1.1.4, p. 5-2) that states "the Mined Geologic Repository shall limit the change in temperature, at 45 cm below the soil surface, to 2°C above what the established naturally occurring pre-emplacement average annual surface temperature is within the footprint of the MGR" (YMP 2001b, 1.3.2.F, p. 1.3-12). This is discussed further in Section 6.3.8.

4.3 CODES AND STANDARDS

ASME Boiler and Pressure Vessel Code - Section II Materials (ASME 1995)

5. ASSUMPTIONS

The following assumptions are used in this analysis. Some of the assumptions presented in this section are considered preliminary, such as the representative location of emplacement drifts and the thickness of stratigraphic units, the waste inventory data, and the waste package dimensions and used in accordance with AP-3.10Q procedure, *Analysis and Models.*

5.1 WASTE EMPLACEMENT

Assumption: The waste package inventory is emplaced simultaneously into all the emplacement drifts. The emplacement area occupies the entire horizontal plane described by the emplacement drifts. This plane is sufficiently large such that any individual drift is not subject to an edge effect.

Basis: These assumptions permits the construction of a 2D model using the ANSYS software for the repository thermal environment. The assumption simplifies the description of waste emplacement and allows symmetrical analogy to be used. Since all the waste is considered emplaced at one time into a centrally located emplacement drift there is no edge effect and the peak temperature values that will be generated will be conservative and this is appropriate for use in this analysis. Used in Section 6.

5.2 ROCK THERMAL GRADIENT

Assumption: The average rock temperature on surface is assumed to be 18.7°C. The in-situ rock thermal gradient is assumed as 0.020°C/m for depth 0 to 150 meters, 0.018°C/m for depth 150 to 400 meters, 0.030°C/m for depth 400 to 536 meters. The in-situ thermal gradient for depth 536 to 700 meters is assumed to be the same as for depth 400 to 536 meters, i.e., 0.030°C/m.

Basis: This assumption is based on the temperature profile in borehole USW G-4 (Sass et al. 1988, p. 48 and Figure 1-12). This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Section 6.2.2.

5.3 LOW TEMPERATURE REPOSITORY PARAMETRIC STUDY

5.3.1 Thermal Load and Emplacement Drift Spacing

Assumption: The base case repository will have a thermal load of 1.45 kW/m. As part of the lower temperature operating modes parametric study, this analysis will investigate a repository with 1.0 kW/m thermal load. The parametric study will further investigate the effect of increased waste package spacing and aging (which serve to reduce the thermal load) and an increased emplacement drift spacing of 120 meters. The parametric study scenarios for the lower temperature operating modes are given in Table 5-1.

Table 5-1. Parametric Study Scenarios for Repository Thermal Loading

Parameter	Base Case [a]	Representative Scenario[b]	Sensitivity Analysis[b]			
			Alternative Scenario One	Alternative Scenario Two	Alternative Scenario Three	Alternative Scenario Four
Drift Spacing (m)	81	81	81	120	81	81
Heat Load (kW/m)	1.45	1.0	1.0	1.45	0.7	0.6 [d]
WP Spacing (m)	0.1	1.9 [c]	0.1	0.1	5.0 [c]	2.0

[a] BSC 2001c, Section 7, p. 109 of 121
[b] BSC 2001e, Section 6.1, pp. 40 and 41 of 126
[c] based on waste inventory, refer to Section 6.3.1
[d] based on waste decay curve, refer to Section 6.3.1

Basis: The existing repository layout has a design thermal load of 1.45 kW/m (BSC 2001c, Section 7, p. 109 of 121) and the *Lower-Temperature Subsurface Layout and Ventilation Concepts* (BSC 2001e, Section 6.1, pp. 40 of 126 and 41 of 126) has published several examples of the lower temperature operating modes that serve as a guide to establish the various scenarios in Table 5-1. This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Section 6 and Attachments I through IX.

5.3.2 Ventilation Duration

Assumption: The duration of the preclosure forced ventilation are assumed to be 25, 50, 100, 125, and 300 years as a function of the parametric study repository modes. The duration of the natural ventilation is assumed to be 250 years. The assumed preclosure ventilation duration for the various scenarios in the parametric study are listed in Table 5-2.

Table 5-2. Parametric Study Ventilation Duration (Years)

Ventilation Type	Base Case	Representative Scenario	Sensitivity Analysis			
			Alternative Scenario One	Alternative Scenario Two	Alternative Scenario Three	Alternative Scenario Four
Forced	[a]	50	50	300	125	125
Natural	N/A	250	250	N/A		

Source: BSC 2001e, Section 6.1, pp. 40 and 41 of 126
[a] maximum of 300 years (Section 4.2.8) in durations of 25, 50, 100, 125 and 300 years

Basis: The *Subsurface Ventilation System Description Document* states that it will support a deferral of closure for up to 300 years (Section 4.2.8). The *Lower-Temperature Subsurface Layout and Ventilation Concepts* (BSC 2001e, Section 6.1, pp. 40 of 126 and 41 of 126) has published several examples of the lower temperature operating modes that serve as a guide to establish the various scenarios shown. Therefore, it is reasonable to assume the stated ventilation durations and it is appropriate for use in this analysis. Used in Section 6, and Attachments I through IX.

5.3.3 Natural Ventilation Flow Rate

Assumption: The air flow rates for the natural ventilation used in the sensitivity analysis are 3 and 1.5 m^3/s for the ventilation periods of 50 to 100 and 100 to 300 years, respectively.

Basis: The air flow rate of natural ventilation varies with temperature, air pressure, and time. The exact determination is complex and beyond the scope of this analysis. However, previous analysis (CRWMS M&O 2000f, Attachment XVII, p. XVII-2) has demonstrated the applicability of these ventilation flowrates and they are appropriate for use in this analysis. Used in Section 6 and Attachments I through IX.

5.4 DOMINANT CONVECTION MODE

Assumption: In the emplacement drift with either forced or natural ventilation, the dominant convection effects are governed by turbulent air flow. Therefore, in the calculation of the convection heat transfer coefficient for both forced and natural ventilation, forced convection (turbulent flow) is applicable.

Basis: A Reynolds number of 4,000 defines the upper boundary of the accepted range for transition from laminar flow to turbulent flow (Holman 1997, p. 221). With forced ventilation, the associated Reynolds number will exceed 4,000, indicating that the flow is turbulent and forced convection is dominant. With natural ventilation, though the flow rate is relatively low, the associated Reynolds number also exceeds 4,000, (CRWMS M&O 2000f, Table 5-8, p. 44) indicating that the flow is also turbulent. Therefore, forced convection is still dominant. Used in Section 6.2.3.3, Table 6-3.

5.5 EMPLACEMENT DRIFT LENGTH

Assumption: Emplacement drifts of 600, 700 and 800 meters in drift split length are considered in this analysis as part of a parametric study to determine the impact of longer emplacement drifts on the peak temperature values.

Basis: This assumption is based on the *Subsurface Facility System Description Document* which assumed a maximum emplacement drift split length of 600 meters (CRWMS M&O 2000b, Section 2.2.2.4, p. 23 of 79). Increasing the split length of the emplacement drift in 100 meter increments is a reasonable dimension to determine the sensitivity of the peak temperature values to increased drift length. This is considered as appropriate for use in this analysis. Used in Section 6.5.1 and Attachments III.

5.6 WASTE PACKAGE INITIAL SURFACE TEMPERATURE

Assumption: At emplacement the initial temperature on the waste package surface is assumed to be 70°C.

Basis: This assumption is based on the average of the initial temperatures from the waste package surfaces as calculated from the *Multiple WP Emplacement Thermal Response – Suite 1* (CRWMS M&O 1998a, Tables 6-1 through 6-4, pp. 26-29) document and supported as conservative by the *Drift Scale Thermal Analysis* (CRWMS M&O 2000i, Table 6-7, p. 50) waste package surface temperatures. Used in Section 6 and Attachments II through IX.

5.7 REPOSITORY GEOLOGIC ASSUMPTIONS

5.7.1 Primary Block Stratigraphic Column Location

Assumption: A representative stratigraphic column is selected at the primary block centroid of the proposed repository in order to quantify the rock properties at this location. The assumed coordinates for this centroid are N232674, E170693 and elevation 1073 meters (invert elevation).

Basis: The centroid is corroborated based on the *Thickness of Stratigraphic Units at the Centroid Location of the Site Recommendation Planning Layout* (CRWMS M&O 2000c). This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Sections 6.2.3.6, 6.7 and Attachments I through IX.

5.7.2 Primary Block Stratigraphic Unit Type and Thickness

Assumption: The thickness of each stratigraphic unit of the primary block representative stratigraphic column (Section 5.7.1) is given in Table 5-3. The topographic surface elevation for the representative stratigraphic column is 1404 meters and the Tpcpv3 unit starts at the 1312 meter elevation.

Basis: The coordinates of the centroid has been assumed in Section 5.7.1 and the stratigraphic units in the geologic column at this location are given in the *Thickness of Stratigraphic Units at the Centroid Location of the Site Recommendation Planning Layout* (CRWMS M&O 2000c). This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Sections 6.2.3.6 and 6.7.

Table 5-3. Primary Block Straigraphic Unit Thickness

T/M Unit	Stratigraphic Unit	Thickness (m)
TCw	Tpcpv3	0
PTn	Tpcpv2	4.9
	Tpcpv1	2.4
	Tpbt4	0.6
	Tpy	4.0
	Tpbt3	4.0
	Tpp	4.6
	Tpbt2	8.5
	Tptrv3	1.8
	Tptrv2	1.2
TSw1	Tptrv1	1.2
	Tptrn	35.4
	Tptrl	8.2
	Tptpul	66.4
TSw2	Tptpmn	37.8
	Tptpll	95.1
	Tptpln	55.2
TSw3	Tptpv3	11.9
CHn1	Tptpv2	5.2
	Tptpv1	15.8
	Tpbt1	3.4
	Calico	44.8
CHn2	Calicobt	15.2

Source: CRWMS M&O 2000c

5.7.3 Lower Block Stratigraphic Column Location

Assumption: A representative stratigraphic column is selected at the lower block centroid of the proposed repository in order to quantify the rock properties at this location. The assumed coördinates for this centroid are N233510, E172093 and elevation 988.60 meters (invert elevation).

Basis: The centroid is based on the *Determination of Stratigraphic Unit Thickness at the Lower Repository Block Centroid* (Elayer 2001, Attachment 2, p. 3 of 4). This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Section 6.7.

5.7.4 Lower Block Stratigraphic Unit Type and Thickness

Assumption: The thickness of each stratigraphic unit of the lower block representative stratigraphic column (Section 5.7.3) is given in Table 5-3a. The topographic surface elevation for the representative stratigraphic column is 1233.0 meters and the rock formation Tpcpv3 unit starts at the 1196.0 meter elevation.

Basis: The coordinates of the centroid has been assumed in Section 5.7.3 and the stratigraphic units in the geologic column at this location are given in the *Determination of Stratigraphic Unit Thickness' at the Lower Repository Block Centroid* (Elayer 2001, Attachment 3, p. 4 of 4). This is the most recent information available and is considered as corroborative information that is appropriate for use in this analysis. Used in Section 6.7.

Table 5-3a. Lower Block Straigraphic Unit Thickness

T/M Unit	Stratigraphic Unit	Thickness (m)
TCw	Tpcpv3	0
PTn	Tpcpv2	3.2
	Tpcpv1	3.1
	Tpbt4	1.5
	Tpy	4.6
	Tpbt3	5.3
	Tpp	7.0
	Tpbt2	8.5
	Tptrv3	2.4
	Tptrv2	1.5
TSw1	Tptrv1	0.2
	Tptrn	49.6
	Tptrl	6.9
	Tptpul	80.3
TSw2	Tptpmn	30.2
	Tptpll	105.3
	Tptpln	52.2
TSw3	Tptpv3	10.0
CHn1	Tptpv2	3.8
	Tptpv1	12.3
	Tpbt1	1.1
	Calico	114.1
CHn2	Calicobt	15.2

Source: Elayer 2001, Attachment 3, p. 4 of 4

5.7.5 Emissivity of Invert Ballast

Assumption: The emissivity of the invert ballast is 0.9 which is equal to an average emissivity value for a concrete surface (Incropera and DeWitt 1985, p. 780).

Basis: In the absence of direct confirming data, concrete emissivity is considered a reasonable representation for the invert ballast and is considered appropriate for use in this analysis. Used in Section 5.9.3 and Attachments I through IX.

5.7.6 Tptpll Thermal Conductivity

Assumption: The thermal conductivity for the Tptpll rock unit values are 1.76 W/m·K and 1.22 W/m·K for the saturated rock condition (≤ 100°C) and the unsaturated rock condition (> 100°C), respectively. These values supercede the previous set of thermal conductivity values for the Tptpll that were 2.02 W/m·K and 1.20 W/m·K for the saturated rock condition and the unsaturated rock condition, respectively.

Basis: The new thermal conductivity values for the Tptpll are provided by the most recently available data (BSC 2001a, Section 6, p. 60) therefore they are appropriate for this analysis. The superceded thermal conductivity values are the historic values that have been used in previous thermal analysis (CRWMS M&O 2000h, Table 4-2, p. 18). Used in Section 4.1.4 and Attachments I through IX.

5.8 WASTE PACKAGE PROPERTIES

5.8.1 Waste Package Inventory

Assumption: The waste inventory of the Commercial Spent Nuclear Fuel (CSNF) is used in the 2D model to generate the thermal load. In the three-waste-package system for the 3D model a 5-DHLW Short/DOE SNF Short waste package is selected for the model. The waste package inventory and the initial heat output of each of these waste packages are shown in Table 5-4. These numbers are used with the time-dependent, heat generation rates (Section 5.8.2) for each waste package type to estimate the overall heat decay percentage with respect to the total initial heat output of the waste package.

Basis: CSNF is used to represent the waste inventory in this analysis because it represents the major portion of the waste inventory and produces the largest heat output overall. The sample 5-DHLW Short is selected since it represents the largest number of DHLW that produces significant heat output. The values that are given in Table 5-4 are based on the *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001b, Worksheet 1, p. 3/49). They represent the latest available information for the number of CSNF waste packages and the representative DHLW waste package and their heat output. This is considered as corroborative information that is appropriate for use in this analysis. Used in Attachments I through IX.

Table 5-4. CSNF Waste Package Inventory and Initial Heat Power

Waste Package Type	Number of Waste Packages	Average Initial Heat Power (kW/package)
21-PWR, Absorber Plates	4,299	11.53
21-PWR, Control Rods	95	3.11
12-PWR, Long	163	9.55
44-BWR, Absorber Plates	2,831	7.38
24-BWR, Thick Absorber Plates	84	0.52
5-DHLW Short/DOE SNF Short	1,052	2.98

Source: BSC 2001b, Worksheet 1, p. 3/49

5.8.2 Waste Package Heat Generation Rates

Assumption: The waste package initial heat power (Table 5-4) is used to give the volumetric heat generation rates listed in Table 5-5. The average time-dependent heat generation rates (kilowatts per waste package) for the waste packages of each type are given as a function of time in Table 5-5. These values are used with the numbers of each type of waste package (Table 5-4) as a basis for determining the time-dependent decay percentage with respect to the initial heat output of the waste packages. Details of the calculation of the time-dependent heat decay percentages are provided in Attachment I. These percentages are then used to determine the volumetric heat generation rates used in the 2D model of the thermal environment (see Attachment I).

Basis: The values that are given in Table 5-5 are based on the *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001b, Table 18, pp. 22/49 to 26/49 and Table 20, pp. 28/49 to 31/49). They represent the latest available information for the CSNF waste packages and the representative DHLW waste package and their heat output. This is considered as corroborative information that is appropriate for use in this analysis. Used in Attachments I through IX.

The *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001d, p. 21/49) transmittal describes the reason for the difference in the Average Initial Heat Power for the 5-DHLW Short waste package as shown in Table 5-4 compared to the value shown in Table 5-5, as follows: When computing the canister-number averaged decay for the Short HLW glass canister, the Idaho Nuclear Technology Engineering Center (INTEC) canisters were not included because they are on a different time grid and because their heat generation rates are small relative to the other DOE SNF waste forms. Note that this results in a slight difference between the values shown in Worksheet 1 (BSC 2001b, Worksheet 1, p. 3/49) and those in Table 20 (BSC 2001b, Table 20, pp. 28/49 to 31/49). This is a single exception for the 5-HLW Short/DOE combination, which has a value of 2.98 kW in Worksheet 1, compared with 2.93 kW in Table 20. This is because the INTEC waste form values are not reported until 2035 and this DOE/SNF waste form arrival date is properly treated in the averaged values provided in Table 20. For Worksheet 1, the INTEC fuel is included in the values at emplacement. The difference is only 50 watts and should be negligible.

Table 5-5. Average Heat Generation Rates for CSNF and DHLW/DOE SNF Waste Packages

Time (year)	21-PWR Absorber Plates (kW/package)	21-PWR Control Rods (kW/package)	12-PWR Long (kW/package)	44-BWR Absorber Plates (kW/package)	24-BWR Absorber Plates (kW/package)	5-DHLW/DOE SNF Short (kW/package)
0.0	11.5284	3.1061	9.5489	7.3775	0.5206	2.9312
0.5 [a]	11.3293	3.0767	9.4084	7.2556	0.5153	2.7972
1.0	11.1460	3.0484	9.2762	7.1430	0.5105	2.6632
5.0	10.0546	2.8403	8.4138	6.4667	0.4733	2.2441
10.0	9.0735	2.6107	7.5931	5.8362	0.4322	1.9850
15.0	8.2723	2.4104	6.9149	5.3126	0.3958	1.7697
20.0	7.5827	2.2325	6.3290	4.8567	0.3636	1.5803
25.0	6.9789	2.0735	5.8174	4.4515	0.3348	1.4127
30.0	6.4443	1.9316	5.3636	4.0955	0.3094	1.3154
35.0	5.9701	1.8043	4.9613	3.7783	0.2866	1.1813
40.0	5.5493	1.6901	4.6044	3.4958	0.2662	1.0604
45.0	5.1710	1.5878	4.2833	3.2437	0.2479	0.9532
50.0	4.8334	1.4956	3.9971	3.0180	0.2318	0.8554
60.0	4.2607	1.3385	3.5136	2.6352	0.2042	0.6948
70.0	3.7974	1.2113	3.1214	2.3272	0.1822	0.5668
80.0	3.4209	1.1078	2.8027	2.0786	0.1646	0.4646
90.0	3.1133	1.0235	2.5426	1.8762	0.1505	0.3830
100.0	2.8629	0.9545	2.3320	1.7125	0.1390	0.3175
125.0 [a]	2.4836	0.8506	2.0125	1.4705	0.1226	0.2062
150.0	2.1042	0.7468	1.6930	1.2285	0.1063	0.1390
200.0	1.7415	0.6474	1.3897	1.0080	0.0926	0.0729
300.0	1.3797	0.5435	1.0925	0.8004	0.0802	0.0313
400.0	1.1659	0.4754	0.9188	0.6811	0.0722	0.0181
500.0	1.0114	0.4225	0.7949	0.5949	0.0660	0.0124
600.0	0.8908	0.3784	0.6985	0.5276	0.0607	0.0094
700.0	0.7932	0.3421	0.6209	0.4734	0.0564	0.0078
800.0	0.7119	0.3106	0.5566	0.4277	0.0526	0.0068
900.0	0.6432	0.2843	0.5024	0.3894	0.0492	0.0061
1000.0	0.5849	0.2619	0.4561	0.3564	0.0466	0.0056
1500.0	0.3990	0.1892	0.3092	0.2517	0.0372	0.0042
2000.0	0.3104	0.1539	0.2396	0.2011	0.0324	0.0036
3000.0	0.2417	0.1262	0.1856	0.1606	0.0283	0.0031
4000.0	0.2157	0.1149	0.1651	0.1439	0.0264	0.0028
5000.0	0.1997	0.1075	0.1528	0.1324	0.0250	0.0027
6000.0	0.1861	0.1014	0.1423	0.1232	0.0235	0.0026
7000.0	0.1743	0.0958	0.1332	0.1148	0.0226	0.0025
8000.0	0.1632	0.0907	0.1246	0.1074	0.0214	0.0024
9000.0	0.1533	0.0859	0.1169	0.1008	0.0204	0.0023
10000.0	0.1441	0.0815	0.1098	0.0942	0.0194	0.0022

Source: BSC 2001b, Table 18, Table 20

[a] Values linearly interpolated for this calculation

5.8.3 Waste Package Physical and Thermal Properties

Assumption: The assumed physical and thermal properties for the waste package construction material used in the analysis are listed in Table 5-6.

Table 5-6. Physical and Thermal Properties for Waste Package

Parameter	Value
Density (kg/m^3)	8690
Thermal Conductivity (W/m·K)	12.53 [a]
Specific Heat (J/kg·K)	435.25 [b]
Emissivity	0.87

Note: [a] Averaged value over the temperature range of 48 to 300°C.
[b] Averaged value over the temperature range of 52 to 300°C.
Source: BSC 2001b, Tables 12 & 13, p. 18/49

Basis: The values that are given in Table 5-6 are for Alloy 22 material, based on the *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001b, Tables 12 & 13, p. 18/49). They are appropriate for the analysis and represent the latest available information for the waste package Alloy 22 material. Used in Attachments I through IX.

5.8.4 Waste Package Dimensions

Assumption: The assumed length and diameter for the representative waste package used in the calculation are listed in Table 5-7.

Table 5-7. Diameter and Length of Various Waste Packages

Type of Waste Package	Diameter (m)	Length (m)
21-PWR	1.564	5.165
44-BWR	1.594	5.165
24-BWR	1.238	5.105
12-PWR	1.250	5.651
5-DHLW/DOE SNF Short	2.030	3.590

Source: BSC 2001b, Table 9, p. 16/49

Basis: The dimensions that are given in Table 5-7 are obtained from the *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001b, Table 9, p. 16/49). They are appropriate for the analysis and represent the latest available information for the waste package dimensions. Used in Attachments I through X.

5.9 ANCILLARY ASSUMPTIONS

5.9.1 Drip Shield Dimensions

Assumption: It is assumed that the drip shield is constructed from titanium that is 15 mm thick and the curved plate section dimension is 1.997 m and the side plate dimension is 2.051 m.

Basis: These dimensions are obtained from the *Design Input for the Engineered Barrier System Environment and Barriers* (BSC 2001b, Table 5, p. 13/49). This information represents the most recent design information that is available. It is considered as corroborative information that is appropriate for use in this analysis. Used in Attachments I through IX.

5.9.2 Emplacement Drift Invert Depth

Assumption: The emplacement drift invert is assumed to have a maximum depth of 0.806 m. The top region occupies the dimension described by the thickness of the transverse support beam which is 12 inches or 0.305 m. Therefore the bottom region depth is 0.501 m.

Basis: These dimension are obtained from the *Emplacement Drift Invert-Low Steel Evaluation* (CRWMS M&O 2000e, Section 7.1, Figure 1, p. 20). This is the most recent design information that is available and it is appropriate to use in this analysis. Used in Section 6.2.3.3 and Attachments I through X.

5.9.3 Emplacement Drift Invert Properties

Assumption: In this analysis, the invert top region composed of a carbon steel framework packed in a ballast material. The aggregate density, specific heat and emissivity of the top region is taken to be similar to concrete. The effective thermal conductivity for the invert top region is considered to be anisotropic. The invert bottom region consists entirely of ballast material. The material properties that are assumed for the invert are listed in Table 5-8.

Table 5-8. Thermal Properties of Invert Material

Property		Invert Top Region	Invert Bottom Region
Density (kg/m^3)		2,323	1,515
Specific Heat (J/kg·K)		1,005	800
Emissivity		0.9	0.9
Thermal Conductivity (W/m·K)	Vertical direction	2.326	0.15
	lateral and axial directions	1.178	

Source: CRWMS M&O 2000g, Section 5.1.7, Table 5-9, p. 23

Basis: In the absence of direct confirming data, concrete emissivity is considered a reasonable representation for the whole ballast material (Section 5.7.5). In order to simplify the material property characteristics of the invert top region, it is treated as one composite material. In order to distinguish the invert bottom region, it is assumed to have different material properties from those of the top region (CRWMS M&O 2000g, Section 5.1.7, Table 5-9, p. 23). Used in Attachments I through IX.

5.9.4 Space Between Waste Package and Invert

Assumption: The assumed minimum gap between the top of the invert and the bottom of the waste package for various waste packages are listed in Table 5-9.

Basis: The dimensions that are given in Table 5-9 are appropriate for the analysis calculations and represent the latest available information (BSC 2001b, Table 10, p. 16/49). It is considered as corroborative information that is appropriate for use in this analysis. Used in Attachments I through IX.

Table 5-9. Gap between Waste Package and Invert for Various Waste Packages

Type of Waste Package	WP Centerline to Top of Invert (mm)	Gap (mm)
21-PWR	1,012	230
44-BWR	1,030	233
5-DHLW/DOE SNF Short	1,281	266

Source: BSC 2001b, Table 10, p. 16/49

5.9.5 Ventilation Air Density

Assumption: The ventilation air density is assumed to be 1.0561 kg/m^3 at 70° F.

Basis: In order to maintain continuity with previous work and association with the air properties given in Section 4.1.2, the air density value from the *Repository Subsurface Waste Emplacement and Thermal Management Strategy* (CRWMS M&O 1998b, Attachment II, p. II-2) is selected for this analysis. The source reference is the table of "Barometric Pressure, Temperature and Air Density at Different Altitudes" from Hartman (1982, Appendix A, Table A-1, p. 713). It is based on 70°F and interpolated between 3500 and 4000 foot elevation. Since this analysis uses a slightly lower elevation from previous thermal calculations, 3519 feet versus 3530 feet, there is a small change in the air density value. The difference is 0.0005, which is the difference between 1.0566 (air density value at the centroid elevation) and 1.0561 (air density value that has been used in previous calculations). At this time, in order to maintain continuity with previous work, i.e., association with Section 4.1.2 air properties, it was decided to use the 1.0561 value as an assumed air density since the difference to the modeling is negligible. This value is considered appropriate for calculations in this analysis and is corroborative information since it serves as a basis for an assumption. Used in Attachments I through X.

6. ANALYSIS/MODEL

The intended use of this analysis is to provide estimates of the Other Factors for the Post-Closure Safety Case as determined by the Screening Criteria for Grading Data attachment in AP-3.15Q and has been assigned Level 2 importance.

The *Lower-Temperature Subsurface Layout and Ventilation Concepts*, noted in Section 5.3.1 of this analysis, describes several possible operating scenarios for a lower-temperature repository which serve as the basis for the five thermal loading strategies that are presented in this analysis.

- The *Base Case* represents the higher temperature operating mode with a thermal load of 1.45 kW/m. This scenario is investigated with the ventilation duration of 25, 50, 100, 200, and 300 years.

- Comparatively, the *Representative Scenario* represents a lower temperature operating mode with a thermal load of 1.0 kW/m. This reduced thermal load is achieved by increasing the spacing of the waste packages. The duration of the ventilation period is 300 years comprised of an initial 50 years of forced ventilation at 15 m^3/s, followed by 50 years, then 200 years of natural ventilation at 3 m^3/s and 1.5 m^3/s, respectively.

- The lower temperature operating mode *Alternative Scenario One* proposes to examine a 1.0 kW/m thermal load generated by a smaller capacity waste package at the minimal waste package spacing of 10 cm. The duration of the ventilation period is 300 years comprised of an initial 50 years of forced ventilation at 15 m^3/s, followed by 50 years, then 200 years of natural ventilation at 3 m^3/s and 1.5 m^3/s, respectively. However, in the 2D model, waste package spacing is not discernable. In 2D, this scenario is the same as the *Representative Scenario* and it is not explicitly modeled. The results from the *Representative Scenario* are considered applicable to *Alternative Scenario One* in the 2D ANSYS analysis.

- *Alternative Scenario Two* serves to compare the *Representative Scenario* with a repository that distributes the waste over a larger area while maintaining the same areal mass loading. For example, a unit length of *Representative Scenario* repository emplacement drift has an area of influence of 81 m^2, hence an areal mass thermal load of 0.012 kW/m^2. The emplacement drift spacing is increased to 120 meters and the thermal load applied is 1.45 kW/m. Therefore, a unit length of emplacement drift has an area of influence of 120 m^2. This is also equivalent to an areal mass thermal load of 0.012 kW/m^2.

- In *Alternative Scenario Three* the impact of a thermal load of less than 1.0 kW/m is considered. This is achieved by increasing the waste package spacing to greater than that which is used in the *Representative Scenario.* A fixed duration of 125 years of forced ventilation is used.

- Aging the waste for an additional 30 years is considered as part of the sensitivity analysis. In *Alternative Scenario Four* the thermal load is reduced by incorporating aging into the modeling. A fixed duration of 125 years of forced ventilation is used.

6.1 THEORETICAL BACKGROUND

Heat transfer mechanisms in a ventilated emplacement drift containing waste packages involve conduction, radiation, and convection. Conductive heat flow occurs within the waste package, the drip shield, the invert, and the surrounding rock whenever there is a thermal gradient. Convective heat transfer occurs between the waste package surface and the ventilating air as well as between the drift wall and the air. Electromagnetic radiation heat transfer occurs directly between the waste package surface and the drift wall and the invert surface prior to placement of the drip shield. After the installation of the drip shield, the electromagnetic radiation heat transfer occurs between the waste package surface and the invert surface and the drip shield inside surface and between the drip shield outside surface, the drift wall, and the invert surface.

6.1.1 Conduction

According to Fourier's law of heat conduction, the general 3D heat conduction equation for a drift can be expressed in Cartesian coordinates as (Holman 1997, Equation 1-3, p. 5):

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q'''=\rho c\frac{\partial T}{\partial t} \qquad \text{(Eq. 6-1)}$$

where
- T = temperature, K
- t = time, s
- k = thermal conductivity, W/m·K
- ρ = density, kg/m^3
- q''' = heat generation rate per unit volume, W/m^3
- c = specific heat, J/kg·K

Fourier's law of heat conduction is embedded in the ANSYS thermal analysis. When a temperature gradient exists in a medium, such as rock or a waste package canister, a heat or energy transfer from the high-temperature region to the low-temperature region is transferred by conduction and calculated by ANSYS with Fourier's law. Details on how the heat conduction calculation is performed by ANSYS are discussed in the ANSYS User's Manual Volume I, *Procedures* (SAS 1995).

6.1.2 Convection

For an air-ventilated drift, the overall effect of convection can be evaluated using Newton's law of cooling (Holman 1997, Equation 1-8, p. 12):

$$q = hA(T_w - T_a) \qquad \text{(Eq. 6-2)}$$

Where
- q = heat flow rate, W
- h = convection heat transfer coefficient, W/m^2·K
- A = convection surface area, m^2
- T_w = drift wall or waste package surface temperature, K
- T_a = ventilation air temperature, K

Newton's law of cooling is embedded in the ANSYS thermal analysis. In addition, this equation is also used in the Excel spreadsheets to calculate the ventilating air temperature. Convection heat transfer occurs at the interface of a solid and a fluid due to a temperature gradient between these two media. In the ANSYS thermal analysis, convection heat transfer is treated as a boundary condition, while in the Excel spreadsheet, it is used in an energy balance calculation. Hence, a convection heat transfer coefficient (h) and a fluid temperature (T_a) are required as inputs. Details on how Newton's law of cooling is used in ANSYS are provided in the ANSYS User's Manual Volume I, *Procedures* (SAS 1995). Discussion on the evaluation of convection heat transfer coefficient for forced and natural ventilation is presented in Section 6.2.3.3.

6.1.3 Radiation

The heat from the waste packages to the drip shield, drift wall, or invert is transferred mainly through thermal radiation. In this analysis, the waste packages are considered to be completely enclosed either by the drift wall and invert prior to the installation of drip shield or by the drip shield and invert after the placement of drip shield (Section 4.2.7). Therefore, the total radiant exchange can be calculated using the following equation based on the Stefan–Boltzmann law (Holman 1997, Equation 1-11, p. 14):

$$q = F_\varepsilon F_G \sigma A \left(T_p^4 - T_w^4\right) \qquad \text{(Eq. 6-3)}$$

where

	q	=	heat flow rate, W
	F_ε	=	emissivity function, dimensionless
	F_G	=	geometric view factor function, dimensionless
	σ	=	Stefan-Boltzmann constant 5.669×10^{-8} W/m^2·K^4 (Section 4.1.1)
	A	=	radiation surface area, m^2
	T_p	=	absolute temperature of the waste package surface, K
	T_w	=	absolute temperature of the drift wall, K

The Stefan–Boltzmann law is embedded in the ANSYS thermal analysis. In contrast to the mechanisms of conduction and convection, where heat transfer through a material medium is involved, electromagnetic radiant heat exchange occurs without involvement of a material medium. Since the heat transfer due to radiation varies with the fourth power of the surface's absolute temperature, the thermal calculation is highly nonlinear. In the ANSYS thermal calculation, radiation heat transfer is handled with the help of a radiation matrix generator. The radiation matrix generator involves generating a matrix of view factors between radiating surfaces and using the matrix as a super-element in the thermal analysis. It is used when the analysis involves two or more surfaces receiving and emitting radiant heat. Use of the radiation super-element in the thermal analysis with ANSYS is optional, and other methods are also available. Details on the thermal analysis involving radiation heat transfer are discussed in the ANSYS User's Manual Volume I, *Procedures* (SAS 1995).

In thermal analyses, these three heat transfer mechanisms are coupled within ANSYS code "automatically" dependent on the number of mechanisms selected. For example, the thermal analysis involving forced or natural ventilation will have all three mechanisms coupled, while the temperature calculation for the postclosure period only involves a coupling of conduction and radiation since natural convection due to air circulation is negligible.

Evaluation of heat exchange in a ventilated drift is a very complex three-dimensional, time-dependent, and coupled heat and fluid flow problem. The ANSYS thermal analysis can only handle heat transfer without fluid flow, at least not directly. Convection is treated as a boundary condition, which is different from many computational fluid dynamics (CFD) codes. To achieve the coupling of heat and fluid flow, a numerical approach is developed by using ANSYS for heat transfer, involving conduction, convection, and radiation, and the Excel spreadsheet for fluid energy balance, involving convection only. Detail on the approach is presented in Section 6.2.3.3.

6.2 METHODOLOGY

6.2.1 Model Configurations

Both two- and three-dimensional models are used in this analysis. In these models, the drip shield is introduced at the time of repository closure. The configurations of these models are described in the following subsections.

6.2.1.1 Two-Dimensional Configuration

In the given inventory of waste packages (Table 5-4) the heat outputs from the different types of waste packages will vary and the waste packages may also be emplaced at a large spacing. These will result in a three-dimensional effect on thermal response. However, in this document the primary thermal analyses were based on two-dimensional models. In two-dimensional models, the total heat load generated by all waste packages emplaced in a single drift at a given time is uniformly smeared over a drift segment analyzed (Section 5.1). Consequently, the temperature variation along the drift segment is neglected, and the results from the analyses are average values. The average temperatures predicted using two-dimensional models, dependent on waste package spacing and the variation of heat outputs, are generally close to the axial average of those predicted by three-dimensional models, though they may be significantly different than the maximum or minimum temperature of three-dimensional calculations. The two-dimensional approach is considered a reasonable approximation. In addition, relative to the three-dimensional approach, it is faster to generate a two-dimensional model and it will take much less time to run. Therefore, two-dimensional models are widely accepted and used in this analysis.

Two different model configurations were used in the 2D ANSYS thermal computations due to the inclusion of the drip shield during the postclosure period. One model is used to calculate the temperatures without the drip shield and the other applies to the model with the drip shield. The first configuration is used for the preclosure period, and the latter for the postclosure period. Figure 6-1 illustrates the model configuration with the drip shield. The model configuration without the drip shield can be constructed by simply removing the drip shield into Figure 6-1. In both configurations, the overall vertical and horizontal dimensions are the same. They contain all of the rock units listed in Table 5-3 (Section 5.7.2), so the vertical dimension is 519.6 m. Based on Assumption 5.1, no heat will flow across two vertical planes, one passing through the center of an emplacement drift and the other through the middle of a rock pillar between two adjacent emplacement drifts. These planes are defined as thermal symmetry planes. No heat will flow perpendicular to a thermal symmetry plane, which serves as a mirror, completely reflecting a system from one side to the other. Because of the thermal symmetry, a model needs to contain only what is bounded by these two vertical planes, and hence, as illustrated in Figure 6-1, half of the drift spacing, 40.5 m (Section 4.2.5), is used for the horizontal dimension. The diameters of the drift and waste package are 5.5 m (Section 4.2.5) and 1.564 m (21-PWR WP) (Section 5.8.4), respectively. Other dimensions such as those for the drip shield and invert are given in Sections 5.9.1 and 5.9.2, respectively.

6.2.1.2 Three-Dimensional Configuration

In order to evaluate temperature variations in the drift axial direction, a 3D analysis needs to be performed. In the 3D analysis, different types of waste packages with different heat decays are placed along the axial direction, resulting in an axial variation in heat distribution. Generally, 3D models give more realistic results, but computational efforts are much greater than those for 2D models. In this analysis due to the limitation of the numerical approach the ventilation simulation relies only on 2D models, while a simple three-waste-package 3D model applicable only to this analysis is used as part of the sensitivity study.

Similar to 2D ANSYS models, two model configurations were used in the 3D ANSYS thermal computations to take into account the configuration change at repository closure due to placing of the drip shield. By taking advantage of the thermal symmetry, only one-half of the affected region is modeled. Two vertical planes that intersect the drift cross-section at two ends of the segment are the symmetry planes and no heat will flow perpendicular to them. Figure 6-2 illustrates the 3D model configuration. A simple three-waste-package system is selected to reduce computational time. The drift segment has three representative waste packages, a 21-PWR, 44-BWR, and DHLW/DOE SNF short. The waste package spacing is determined by the linear thermal load. As a result, the 1.0 kW/m thermal load combined with the simple three-package-system has limitations for the combination of the waste package arrangement, therefore precise agreement with the 2D scenario spacing is not achieved. The vertical and horizontal dimensions, other than the space between the waste packages and the bottom gap to the top of the invert, are the same as those for the 2D models. Referring to Figure 6-2, the 3D model drift length and waste package spacing are calculated as follows:

- The initial linear heat load over this segment is equal to 1.0 kW/m. The initial heat outputs of 21-PWR, DHLW, and 44-BWR packages are 11.53 kW, 2.98 kW, and 7.38 kW, respectively (Section 5.8.1). Therefore, the segment length is equivalent to the sum of the waste package initial heat outputs which is 21.89 m.

- The 21-PWR waste package spacing is a function of the initial linear heat load spread over a sub-segment that contains only the 21-PWR waste package. The initial linear heat load over this sub-segment is set to be 1.0 kW/m, so the corresponding length is 11.53 m. The 21-PWR package is located between a virtual 21-PWR package ("hot" side) and a DHLW package ("cold" side). The "hot" side spacing is twice that of the "cold" side in order to achieve a uniform temperature distribution. Applying thermal symmetry, only half of the spacing on the "hot" side is shown in the model. Hence, the "cold" side spacing is defined by the difference of the sub-segment length less the waste package length, divided in half, which is 3.18 m.

- The gap between the DHLW and 44-BWR waste packages is set to 0.1 m, the minimum waste package spacing (Section 4.2.6).

- The spacing between two 44-BWR waste packages (one shown in the model and the other virtual package not included due to thermal symmetry) is a function of the initial linear heat load spread over a drift sub-segment that contains both the 44-BWR and DHLW waste packages since the space between the 44-BWR and the DHLW is fixed at 0.1 m. The initial linear heat load over this sub-segment is set at 1.0 kW/m. So the length of this sub-segment is equivalent to the sum of the initial heat outputs of the 44-BWR and the DHLW or 10.36 m. Hence, the half gap is determined as follows:

  Half of the gap between two adjacent 44-BWR packages = 10.36 - 5.17 - 3.59 - 0.1 = 1.5 m

Most of the dimensions and boundary conditions of the 3D configuration are illustrated in Figure 6-2. It is noted that this three-dimensional model only serves as an example for the sensitivity study purpose and should not be misjudged as a representative of the waste stream. This is why only three waste packages are modeled. The linear heat load used is 1.0 kW/m and this is the only control parameter. The variable parameters are waste package spacing and waste package emplacement sequence. Consequently, within this drift segment, several different waste emplacement arrangements can be developed to represent a similar condition. The number of arrangements will increase with the drift segment length, or the number of waste packages involved.

The dimensions and boundary conditions of the 3D configuration are illustrated in Figure 6-2 and Table 6-1 summarizes the calculation.

Table 6-1. Waste Package Spacing

Occupant	Length (m)	Thermal Output (kW)
Half spacing to adjacent waste package	3.18	11.53
21 PWR	5.17	
spacing	3.18	
DHLW	3.59	2.98
Spacing	0.1	
44 BWR	5.17	7.38
Half spacing to adjacent waste package	1.50	
Total	21.89	21.89

6.2.2 Initial and Boundary Conditions

Initial rock temperature at the emplacement drift horizon is calculated using the in-situ rock thermal gradient provided in Section 5.2 as follows:

$$18.7+(150)(0.020)+(328.25-150)(0.018) = 24.91°\mathrm{C} \cong 25°\mathrm{C}$$

Constant temperatures are set on both the upper and lower boundaries of the model, as indicated in Figures 6-1 and 6-2. These boundary temperatures are determined based on Section 5.2. The temperature of 29.8°C on the lower boundary is calculated based on the temperature on the surface, 18.7°C, and the rock thermal gradient provided in Section 5.2 as follows:

$$18.7+(150)(0.020)+(400-150)(0.018)+(519.6-400)(0.030) = 29.79°\mathrm{C} \cong 29.8°\mathrm{C}$$

Due to thermal symmetry, both lateral boundaries of the models are set to be adiabatic (Figures 6-1 and 6-2). For the 3D models, both axial boundaries are also set to be adiabatic (Figure 6-2).

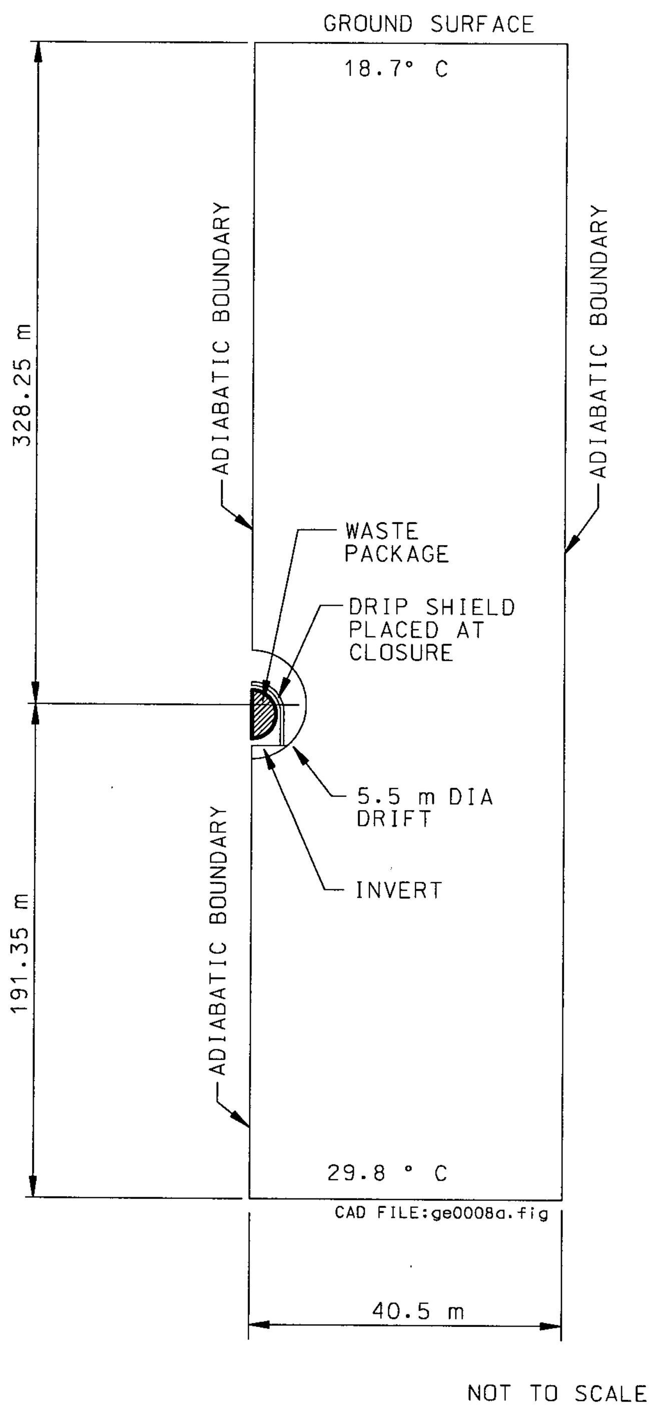


Figure 6-1. Dimensions and Boundary Conditions of 2D ANSYS Model

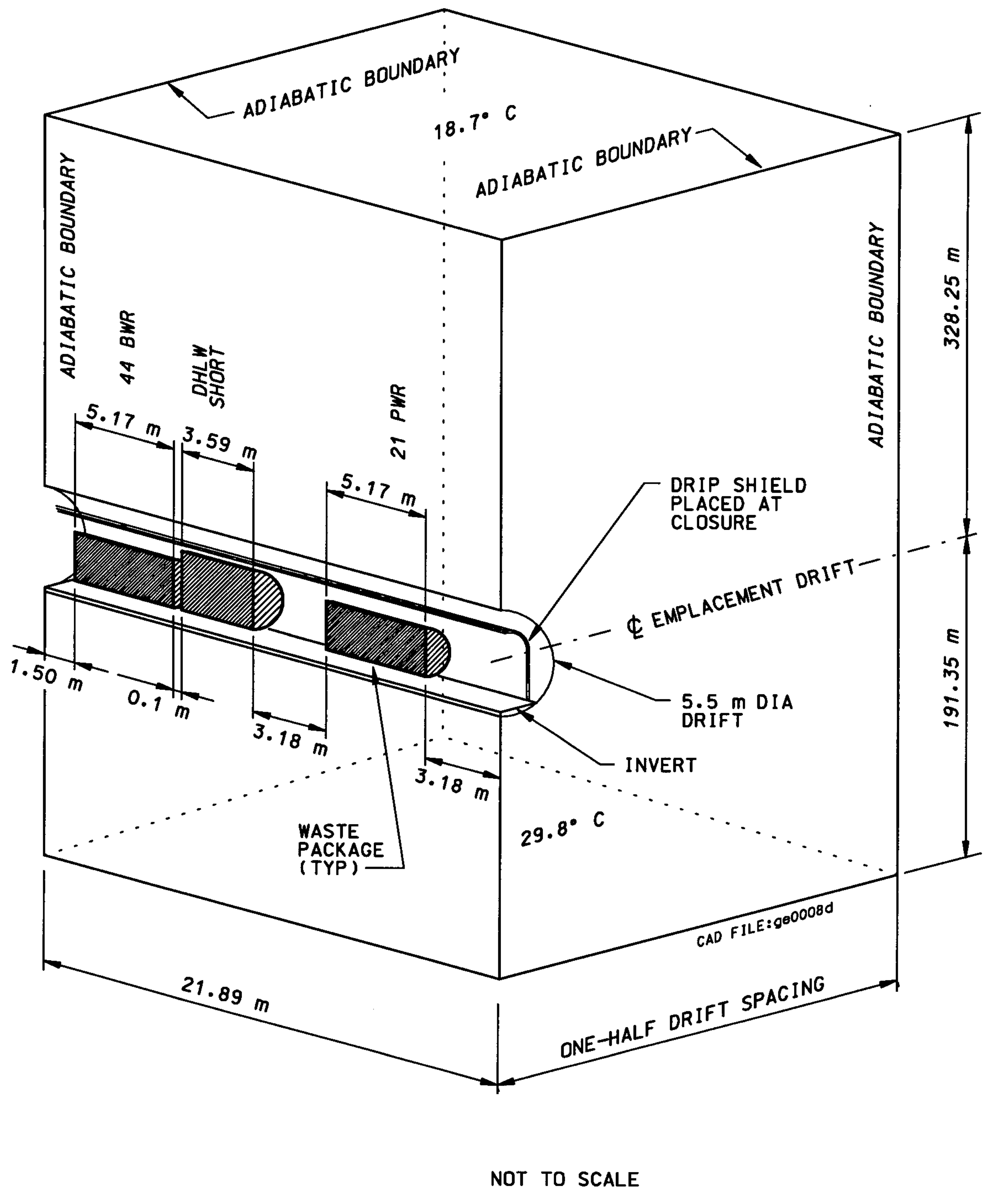


Figure 6-2. Dimensions and Boundary Conditions of 3D ANSYS Model

6.2.3 Approach Used in the Model Simulations

6.2.3.1 Forced or Natural Ventilation

As stated in Section 6.1.3, determination of heat exchange in a ventilated drift is a complex three-dimensional, time-dependent, and coupled heat and fluid flow problem. Due to the limitation in ANSYS thermal analysis, a numerical approach using the ANSYS computer code together with an Excel spreadsheet is employed. A description of the approach follows:

First, an emplacement drift, subjected to continuous ventilation, with a length of L (see Sections 4.2.9 and 5.5 for the effective length of air flow) is divided into a finite number of drift segments, m. During modeling, the drift segments are treated as a series of connected elements, and the exit air temperature at a segment is used as an intake air temperature for the subsequent segment. The ventilating air, wall, and waste package temperatures at a specific modeling time are assumed to be constant over the length of a drift segment. Theoretically, the length of drift segments should be selected as short as possible so that the changing air, wall, and waste package surface temperatures along a drift segment can be reasonably represented by their averaged constants. But practically, a relatively long drift segment can be used as long as the results are not very sensitive to the drift segment length selected. If the length of a drift segment is changed, the number of drift divisions will be changed accordingly. The number of computational runs is equal to the number of drift divisions for each ventilation case analyzed.

In order to reduce the computational effort, a drift split length was divided into a number of 100-meter long segments for all the scenarios analyzed in this study excluding one. In the one exceptional case, the drift split length was divided into 9 segments of various segment lengths from 25 meters to 100 meters to investigate the impact of an increased number of segments and variable segment length on the predicted thermal response.

Second, the ventilation time, t_{vent}, is partitioned into a number of time-steps, n, for each computational run. The size of each time-step, Δt_i, $i=1,2,\cdots,n$, is determined based on experience regarding the degree of computational accuracy because the ventilating air temperature in a drift segment is fixed over each time-step and the heat decay of waste packages in the emplacement drifts varies linearly over the same time-step. Several factors are considered when determining the time-step size, Δt_i, $i=1,2,\cdots,n$. The first is the heat generation rate of the waste packages in the emplacement drifts because the heat generated by the waste packages varies with time. Initially, more heat may be generated and transferred to the rock mass. With time, the heat decay rate will drop, and less heat will be generated. Therefore, a small time-step is required at the beginning and a relatively larger time-step can be justified for the later time period. The second factor is the air temperature variation with time, which is related to the ventilation air quantity and the waste package decays. The third factor is the variation of convection heat transfer coefficients with time. When a change in the convection heat transfer coefficient occurs due to a change in the assumed flow rate, the time step size needs to be reduced. In this analysis, the duration of the time-steps selected varies from 1 year to 50 years for a modeling period of up to 300 years (Section 4.2.8) that includes the duration of the forced and natural ventilation. Within each time step, the minimum and maximum sizes of sub-steps are defined to further control the accuracy of the calculations. The size of the first sub-step is equal to the minimum one. The sizes of other sub-steps are determined "automatically" by ANSYS based on computational convergence criteria, and may vary from a fraction of a second to over 10 years.

Third, after the selection of the segment length and the time-step size, the ANSYS program is executed over the total ventilation duration for a total number of *m* times (finite number of drift segments) for each ventilation case analyzed. The resulting wall temperatures for the currently operated upon modeled drift segment are utilized to calculate the average exhaust air temperatures of the segment by means of Newton's cooling law (Equation 6-2). These exhaust air temperatures are then used as the intake air temperatures for the subsequent drift segment. This process is repeated until the computational run for the last drift segment is completed.

The approach described above is applicable to all the 2D cases investigated in this analysis. The following outlines the process of using Newton's cooling law (Equation 6-2) and energy balance (Equation 6-6 below) to calculate the exhaust air temperatures and the rates of heat removal in a drift segment.

The rates of heat removed from the drift wall and the waste package surface in a drift segment by ventilation are determined using Newton's cooling law (Holman 1997, Equation 6-3, p. 286) as follows:

$$q_w^i = hA_w\left(T_{wa}^i - T_{ain}^i\right) \qquad \text{(Eq. 6-4)}$$

and

$$q_p^i = hA_p\left(T_{pa}^i - T_{ain}^i\right) \qquad \text{(Eq. 6-5)}$$

where

q_w^i	=	rate of heat removed from drift wall at time step *i*, W
q_p^i	=	rate of heat removed from waste package surface at time step *i*, W
h	=	convection heat transfer coefficient, W/m^2·K
A_w	=	drift wall area, m^2
A_p	=	waste package surface area, m^2
T_{wa}^i	=	average drift wall temperature at time step *i*, K
T_{pa}^i	=	average waste package surface temperature at time step *i*, K
T_{ain}^i	=	intake air temperature at time step *i*, K

The exhaust air temperature is calculated based on Holman (1997, Equation 6-1, p. 286) as,

$$T_{aout}^i = T_{ain}^i + \frac{q_w^i + q_p^i}{\dot{m}c} = T_{ain}^i + \frac{q_w^i + q_p^i}{Q\rho c} \qquad \text{(Eq. 6-6)}$$

where

T_{aout}^i	=	exhaust air temperature at time step *i*, K
T_{ain}^i	=	intake air temperature at time step *i*, K
q_w^i	=	rate of heat removed from drift wall at time step *i*, W
q_p^i	=	rate of heat removed from waste package surface at time step *i*, W
m'	=	rate of air mass, kg/s ($m'=Q\rho$)
Q	=	ventilation air flow rate, m^3/s

ρ	=	density of air, kg/m^3
c	=	specific heat of air, J/kg·K

It should be noted that using Equations 6-4 and 6-5 will most likely overstate the rates of heat removed from the drift wall and the waste package surface, consequently overstate the increase of ventilating air temperature estimated based on Equation 6-6. To enhance the calculation of the heat removal rates, some adjustments are needed. Three types of adjustments, so-called corrections, are discussed here. The first is related to the axial variation of air temperature and it is called the spatial correction. With the spatial correction, the intake air temperature, T^i_{ain}, in Equations 6-4 and 6-5 is substituted by the average of the intake and exhaust air temperatures of a given drift segment at a given time step to calculate the rates of heat removed by ventilation,

$$q^i_{rm} = \overline{q}^i_w + \overline{q}^i_p = hA_w\left(T^i_{wa} - T^i_{aa}\right) + hA_p\left(T^i_{pa} - T^i_{aa}\right) \qquad \text{(Eq. 6-7)}$$

where T^i_{aa} = average of intake and exhaust air temperature in a drift segment at at time step i, defined as

$$T^i_{aa} = \frac{T^i_{ain} + T^i_{aout}}{2} \qquad \text{(Eq. 6-8)}$$

where

T^i_{ain}	=	intake air temperature at time step i, K
T^i_{aout}	=	exhaust air temperature at time step i, K

This adjustment is considered because the temperatures of the drift wall and the waste package surface obtained from ANSYS model are the average over the particular drift segment that is being analyzed, therefore, the average ventilating air temperature should be used to reasonably estimate the ventilation heat removal rate.

The second adjustment is called the temporal correction, which is related to the variation of air temperature in time. This correction is achieved by substituting the intake air temperature, T^i_{ain}, in Equations 6-4 and 6-5 by the average of the intake air temperatures of a given drift segment at the previous time step *i-1* and the current time step *i*,

$$T^i_{aa} = \frac{T^{i-1}_{ain} + T^i_{ain}}{2} \qquad \text{(Eq. 6-9)}$$

where

T^{i-1}_{ain}	=	intake air temperature at time step *i-1*, K
T^i_{ain}	=	intake air temperature at time step i, K

The temporal correction is considered because in the ANSYS calculations the convection air temperature is linearly interpolated between two sequential time steps. Without this adjustment, the heat removal rate will likely be understated.

The third correction is the combination of the spatial and temporal corrections. With this correction, the intake air temperature, T^i_{ain}, in Equations 6-4 and 6-5 is substituted by the average of the intake air temperatures of a given drift segment at the previous time step *i-1* and the current time step *i* and the exhaust air temperature at the current time step *i*,

$$T_{aa}^{i} = \frac{T_{ain}^{i-1} + T_{ain}^{i} + T_{aout}^{i}}{3} \qquad \text{(Eq. 6-10)}$$

where T^{i-1}_{ain} = intake air temperature at time step *i-1*, K
T^{i}_{ain} = intake air temperature at time step *i*, K
T^{i}_{aout} = exhaust air temperature at time step *i*, K

In this analysis, the ventilating air temperatures presented are predicted based on Equation 6-6. The rates of heat removed by ventilation are estimated using the combined spatial and temporal correction (Equation 6-10) for all the cases analyzed. As part of a sensitivity study, the rates of heat removal using the spatial correction are also calculated and presented for the *Representative Scenario*.

6.2.3.2 Ventilating Air Flow Rates and Duration

In the preclosure period, forced ventilation with a constant air flow rate of 15 m^3/s (Section 4.2.4) is used in the calculations for the ventilation durations of 25, 50, 100, 125, or 300 years (Section 5.3.2). Natural ventilation air flow rates of 3 and 1.5 m^3/s are used in the *Representative Scenario* and *Alternative Scenario One* for durations of 50 and 200 years, respectively. Table 6-2 summarizes the variations of the ventilation air flow rates with respect to the duration of the ventilation period for the different cases analyzed.

Table 6-2. Repository Ventilation Flow Rates for Each Scenario

Flow Rate (m^3/sec)	Base Case	Representative Scenario	Alternative Scenario One	Alternative Scenario Two	Alternative Scenario Three	Alternative Scenario Four
Forced @ 15	25, 50,100, 300	50	50	300	125	125
Natural @ 3	N/A	50	50	N/A		
Natural @ 1.5		200	200			

6.2.3.3 Calculation of Convection Heat Transfer Coefficient

As stated previously, an air flow rate of 15 m^3/s is considered for the forced ventilation (Section 4.2.4), and the flow rates of 3 and 1.5 m^3/s are used for the natural ventilation (Section 5.3.3). These flow rates are used to determine the convection heat transfer coefficients for each ventilation flowrate. The following equations were employed in calculating the convection heat transfer coefficients:

Air flow velocity, v, based on *Fluid Mechanics* (White 1986, Equation 1.21, p. 16):

$$v = \frac{Q}{A_{flow}} \qquad \text{(Eq. 6-11)}$$

where Q = ventilation air flow rate, m^3/s
A_{flow} = area of flow cross-section, m^2

Reynolds No., *Re* (Holman 1997, Equation 5-2, p. 220):

$$\mathrm{Re} = \frac{\rho v D_h}{\mu} \qquad \text{(Eq. 6-12)}$$

where ρ = density, kg/m^3
v = air flow velocity, m/s
D_h = hydraulic diameter of the cross section, m, defined as (Perry et al. 1984, Table 5-8, p. 5-25)

$$D_h = 4r_h = \frac{4A_{flow}}{P} \qquad \text{(Eq. 6-13)}$$

P = wetted perimeter, m
A_{flow} = area of flow cross section, m^2
μ = dynamic viscosity of air, kg/m·s

Nusselt No., *Nu* (Perry et al. 1984, Equation 10-60, p. 10-17):

$$Nu = 0.020\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{D_w}{D_p}\right)^{0.53} \qquad \text{(Eq. 6-14)}$$

where Re = Reynolds number, dimensionless
Pr = Prandtl number, dimensionless
D_w = drift diameter, m
D_p = waste package diameter, m

The expression (Eq. 6-14) is for calculation of heat transfer in turbulent flow in a smooth annulus, and considered applicable for this calculation.

Convection heat transfer coefficient, *h* (Holman 1997, Equation 5-107, p. 261):

$$h = \frac{kNu}{D_h} \qquad \text{(Eq. 6-15)}$$

where k = thermal conductivity, W/m·K
Nu = Nusselt Number, dimensionless
D_h = hydraulic diameter of the cross section, m

Table 6-3 summarizes the results of calculation of the convection heat transfer coefficients for the air flow rates of 1.5 m^3/s and 3 m^3/s (Section 5.3.3), and 15 m^3/s (Section 4.2.4). The values of the air properties for thermal conductivity, specific heat, dynamic viscosity, and Prandtl number, used to calculate the convection heat transfer coefficients are given in Section 4.1.2, Table 4-1. The air density is obtained from Section 5.9.5. Dimensions used for the emplacement drift and the invert are from Sections 4.2.5 and 5.9.2 respectively.

Table 6-3. Convection Heat Transfer Coefficients for Ventilation Flow Rates

Parameter	Source	Value		
Air Flow Rate (m^3/s)	Section 5.3.3, 4.2.4	1.5	3	15
Hydraulic Diameter (m)	Eq. 6-13	3.62	3.62	3.62
Area in Flow (m^2)	calculated	19.68	19.68	19.68
Air Flow Velocity (m/s)	Eq. 6-11	0.08	0.15	0.76
Reynolds No.	Eq. 6-12	15,869	31,737	158,685
Nusselt No.	Eq. 6-14	79.64	138.66	502.48
Convection Heat Transfer Coefficient ($W/m^2 \cdot K$)	Eq. 6-15	0.57	1.00	3.62

Note: refer to Attachment X, pp. x-2, x-3 for sample calculation

6.2.3.4 Inclusion of the Drip Shield

If a drip shield is placed at the repository closure (Section 4.2.7), the configurations for both 2D and 3D configurations will change. This geometric change can be represented by using a so-called element birth and death scheme in ANSYS. With the element birth and death scheme, a single configuration can be employed to calculate the temperatures in both the preclosure and postclosure periods. The approach is described below.

First, a model is developed in which the drip shield is included. Second, when calculating the temperatures for the preclosure period, the elements which represent the drip shield are set to be "dead" by assigning a very low value of mass in ANSYS. In this step, the radiation heat transfer occurs from the waste package surface directly to the drift wall and invert surface, so the radiation matrix used in the ANSYS representations need to be generated accordingly. Third, when calculating the temperatures for the postclosure period, the "dead" elements that represent the drip shield during the preclosure are set to be "alive" by assigning a real value of mass. In this step, the radiation heat flow occurs from the waste package surface to the interior surface of the drip shield and invert, and from the drip shield exterior surface to the drift wall and the invert surface outside the drip shield. A different radiation matrix is generated in this step to reflect the change in the geometry and heat flow networks.

6.2.3.5 Heat Decay Values of Waste Packages

The heat decay values of waste packages used in the calculation are in the form of volumetric heat generation rates (watts per unit volume). These volumetric heat generation rates are calculated based on the initial linear heat loads, the average percentage values of initial heat, and the waste package volume. These values, other than the surface heat flux values, are used when the convection on the waste package surface is considered in the simulations because only one boundary condition, either a convection boundary or a heat flux boundary, can be prescribed in ANSYS. The heat flux boundary condition can be equivalently substituted by applying the volumetric heat generation rate to present the heat load generated by the waste packages. For post-processing purposes, the values of volumetric heat generation rate (Section 5.8.2) are converted to a unit for time in years by multiplying a conversion factor of 3.1536×10^{7} seconds/year (refer to Attachment I)

As part of the sensitivity study for the flexible repository design, two initial heat loads, 1.0 kW/m and 1.45 kW/m, are used (Section 5.3.1). In addition, a case with additional 30 years of waste aging is considered. To analyze this case, the decay values of waste is set to be equal to those at 30 years older for other cases without additional waste aging, that is:

$$P_{w/\ aging}(t) = P_{w/o\ aging}(t+30) \qquad \text{(Eq. 6-16)}$$

where $P_{w/\,aging}$ = heat power of waste with additional aging, kW/package
$P_{w/o\,aging}$ = heat power of waste without additional aging, kW/package
t = time, year

Figure 6-3 illustrates the heat decay curve for waste with additional 30 years of aging in the form of initial linear heat load (kW/m), compared with those for waste without additional aging. It is seen that the aging curve is obtained by moving the non-aging curve to the left by 30 years. Details of how the volumetric heat generation rates are determined are presented in Attachment I.

As stated in Section 6.2.1.2, ventilation cannot be explicitly simulated in 3D models using ANSYS thermal analysis, which is part of the ANSYS software family. To account for its effects on temperatures in 3D models, the heat decay values of waste packages during the preclosure period are adjusted. The adjusted heat decay values are obtained by multiplying the regular values by a factor of $(1-f_{ve})$, where f_{ve} is the ventilation efficiency calculated based on the spatial correction for the corresponding case (refer to Attachment I, p. I-5). For illustrative purposes, Figure 6-4 shows the regular and adjusted heat generation rates for a 21-PWR waste package. The adjusted heat decay values for other types of waste packages are determined similarly, and presented in Attachment I.

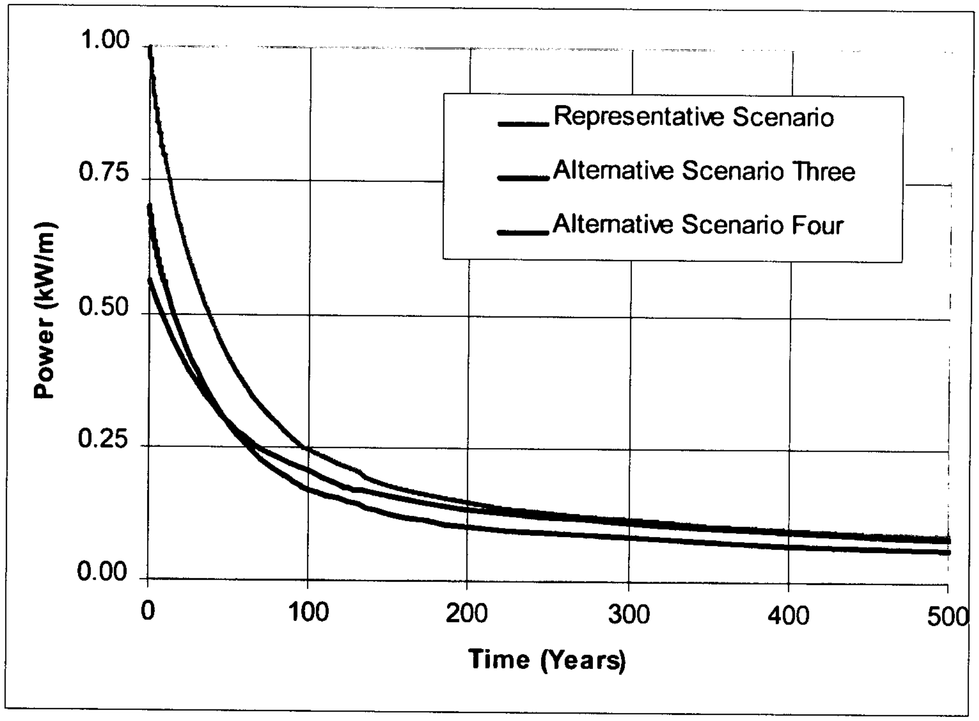


Figure 6-3. Waste Inventory Heat Decay Curves

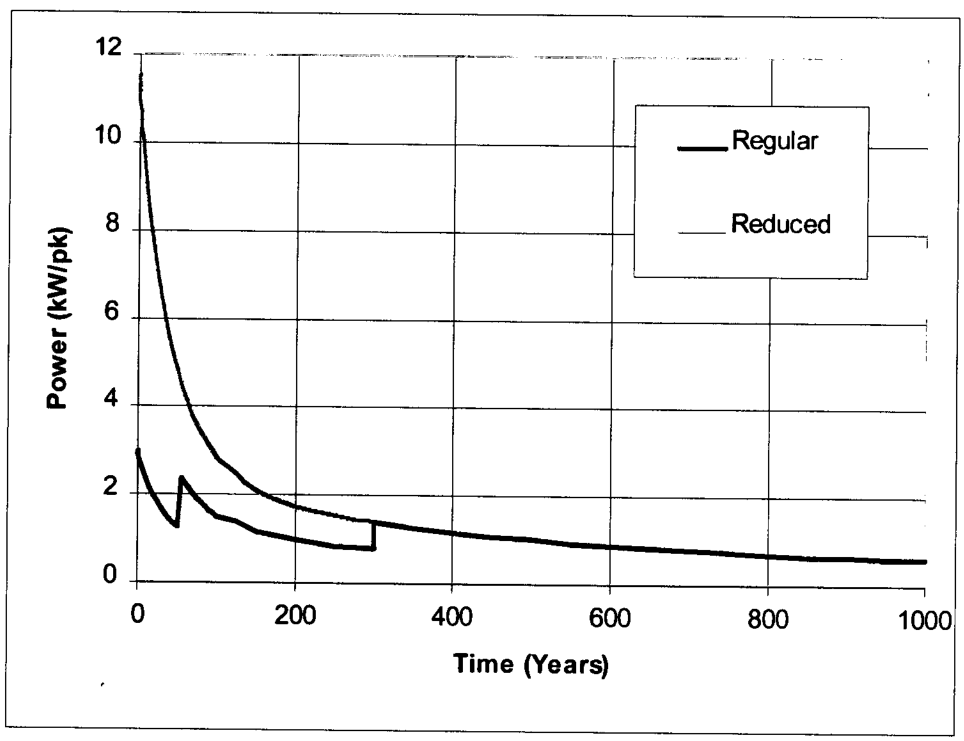


Figure 6-4. 21 PWR Heat Decay Curve Adjusted for Ventilation Efficiency in the 3D Model

6.2.3.6 Primary Block Stratigraphic Column Location and Composition

The stratigraphic column which represents the typical rock strata used in this analysis is located at the centriod of the primary block. The coordinates of this centriod are N232674, E170693 and the invert elevation is 1073.00 meters at this location (Section 5.7.1). The origin of the vertical axis, referred to as the y-coordinate, is located at the emplacement drift springline. The springline is at 2.75 meters above the invert, which is equal to the radius of the emplacement drift (Section 4.2.5). Therefore the springline elevation is 1075.75 meters. The topographic elevation (surface) is 1404 meters (Section 5.7.2). Therefore, the stratigraphic column height from repository springline to the surface is 328.25 meters. The Tpcpv3 unit represents the start of the rock formation at elevation 1312 meters (Section 5.7.2). Therefore the overburden is 92 meters thick. Table 6-4 shows the Y-coordinate value for each stratigraphic unit and the corresponding elevation.

Table 6-4. Primary Block Depth and Coordinates of Stratigraphic Unit

T/M Unit	Stratigraphic Unit	Thickness (m)	Y - Coordinate (m)	Elevation (m)
N/A	Overburden	92	328.25	1404
TCw	Tpcpv3	0	236.25	1312
PTn	Tpcpv2	4.9	236.25	1312
	Tpcpv1	2.4	231.35	1307.1
	Tpbt4	0.6	228.95	1304.7
	Tpy	4.0	228.35	1304.1
	Tpbt3	4.0	224.35	1300.1
	Tpp	4.6	220.35	1296.1
	Tpbt2	8.5	215.75	1291.5
	Tptrv3	1.8	207.25	1283
	Tptrv2	1.2	205.45	1281.2
TSw1	Tptrv1	1.2	204.25	1280
	Tptrn	35.4	203.05	1278.8
	Tptrl	8.2	167.65	1243.4
	Tptpul	66.4	159.45	1235.2
TSw2	Tptpmn	37.8	93.05	1168.8
	Tptpll	95.1	55.25	1131
	Tptpln	55.2	-39.85	1035.9
TSw3	Tptpv3	11.9	-95.05	980.7
CHn1	Tptpv2	5.2	-106.95	968.8
	Tptpv1	15.8	-112.15	963.6
	Tpbt1	3.4	-127.95	947.8
	Calico	44.8	-131.35	944.4
CHn2	Calicobt	15.2	-176.15	899.6
	Total	*519.6*		

6.3 LOWER TEMPERATURE REPOSITORY SCENARIOS

6.3.1 Repository Scenarios Used for Sensitivity Analysis

As described at the start of Section 6, this analysis will present a *Base Case* higher temperature repository and compare the peak temperature values with those of the lower temperature *Representative Scenario.* A sensitivity analysis on the *Representative Scenario* repository will examine the impact to the peak temperature values when changes are made to the thermal load, the emplacement drift spacing, the waste package spacing and aging of the waste. These scenarios and parameters are given in Table 6-5 (from Sections 4.2.6, 5.3.1, 5.3.2, 5.3.3).

Table 6-5. Repository Thermal Loading and Ventilation Flow Rates

Parameter	Base Case	Representative Scenario	Sensitivity Analysis			
			Alternative Scenario One	Alternative Scenario Two	Alternative Scenario Three	Alternative Scenario Four
Drift Spacing (m)	81	81	81	120	81	81
Heat Load (kW/m)	1.45	1.0	1.0	1.45	0.7	0.6 [b]
WP Spacing (m)	0.1	1.9	0.1	0.1	5.0	2.0
Ventilation						
Rate (m^3/sec)	Years					
Forced @ 15	[a]	50	50	300	125	125
Natural @ 3	N/A	50	50	N/A		
Natural @ 1.5		200	200			

[a] Section 6.2.3.2 [b] Attachment 1, Table I-1 (30 year decay percentage rounded off to 60%)

6.3.2 Peak Temperature Values For Repository Alternatives

For the thermal loading scenarios tabled in Section 6.3.1, the maximum temperature and the corresponding occurrence time based on ANSYS calculations are given in Table 6-6. The maximum values are calculated for the waste package, the drift wall, the PTn geologic formation and the zeolite geologic formation. Refer to the appropriate attachment (identified along the top row in Table 6-6) for the detailed calculations and the temperature curve plots.

Note that the *Representative Scenario* and *Alternative Scenario One* are combined in Table 6-6. The thermal load and the ventilation period is the same for both these cases and, in the 2-dimensional model, waste package spacing is not a factor. Therefore they are not distinguishable in a 2D model. Attachment III presents the data that applies to both these cases.

In Table 6-6, the *Base Case* scenario is subdivided into five cases that are a function of the duration of the ventilation period. These subcategories are 25, 50, 100, 200, and 300 years of continuous ventilation at 15 m^3/sec (Sections 5.3.2 and 4.2.4). Figure II-4 from Attachment II illustrates the Drift Wall Temperature curves. Similarly, Figure II-5 from Attachment II illustrates the Waste Package Surface Temperature curves for the stated duration of forced ventilation. The peak temperature values of the PTn and the zeolite formations for the ventilation period of 300 years are determined from Figure II-6, Rock Temperatures, in Attachment II. Similarly, the peak temperature values of the PTn and the zeolite formations for the ventilation periods 25, 50, 100 and 200 years can be found from the Excel spreadsheet file tm2db.xls located by DTN: MO0107MWDTEM05.011 in the Technical Data Management System. The Middle-of-Pillar temperature curves are given in Attachment II, Figure II-7.

The combined *Representative Scenario* and *Alternative Scenario One* peak temperature values are located in Attachment III. The Drift Wall Temperature is obtained from Figure III-4 and it corresponds to the 500-600 m emplacement drift value. Similarly, the Waste Package Surface value is selected from Figure III-5. The peak temperature values of the PTn and the zeolite formations are determined from Figure III-6, Rock Temperatures.

Similarly, the corresponding figures in Attachment IV, V, and VI will provide the peak temperature values for *Alternative Scenarios Two, Three, and Four*, respectively.

Table 6-6. Summary of 2D Model Peak Temperatures

Attachment		II					III	IV	V	VI
Scenario		Base Case					Representative Scenario[a]	Alternative Scenario Two	Alternative Scenario Three	Alternative Scenario Four
Parameter		Thermal Load (kW/m)/Drift Spacing (m)/Ventilation (yrs)								
		1.45/81/25,**50**,100,200,300					**1.0**/81/[b]	**1.45**/120/300	**0.7**/81/125	**0.6**/81/125
WP Surface Temperature	°C	233	176	125	103	93	83	87	69	82
	Yr	*41*	*67*	*134*	*548*	*728*	*483*	*5*	*348*	*418*
Drift Wall Temperature	°C	222	165	117	98	90	79	78	65	78
	Yr	*42*	*73*	*371*	*588*	*768*	*548*	*568*	*468*	*518*
Mid Pillar Temperature	°C	99	95	89	80	74	N/A			
	Yr	*695*	*774*	*842*	*968*	*1238*				
PTn Temperature	°C	57	55	51	48	45	41	38	36	40
	Yr	*1402*	*1409*	*1500*	*1593*	*1838*	*1540*	*1738*	*1500*	*1510*
Zeolite Temperature	°C	59	58	55	51	49	45	42	41	45
	Yr	*893*	*933*	*1002*	*1238*	*1338*	*1138*	*1338*	*1040*	*1108*

[a] For 2D ANSYS analysis Representative Scenario and Alternative Scenario One are combined

[b] Forced ventilation: 0 - 50 years @15 m^3/s; natural ventilation: 50 - 100 years @ 3 m^3/s, 100 - 300 years @ 1.5 m^3/s

The temperature curves associated with the peak temperature values from Table 6-6 are shown in the following two figures.

Figure 6-5 shows the waste package surface temperature curves. They are found in Attachment II, Figure II-5 for both Base Case curves; Attachment III, Figure III-5, the 500 - 600 m. curve for the Representative Scenario; Attachment IV, Figure IV-4 for the Alternative Scenario Two curve; Attachment V, Figure V-4 for the Alternative Scenario Three curve; Attachment VI, Figure VI-4 for the Alternative Scenario Four curve.

Figure 6-6 shows the drift wall temperature curves. They are found in Attachment II, Figure II-4 for both Base Case curves; Attachment III, Figure III-4, the 500 - 600 m. curve for the Representative Scenario; Attachment IV, Figure IV-4 for the Alternative Scenario Two curve; Attachment V, Figure V-4 for the Alternative Scenario Three curve; Attachment VI, Figure VI-4 for the Alternative Scenario Four curve.

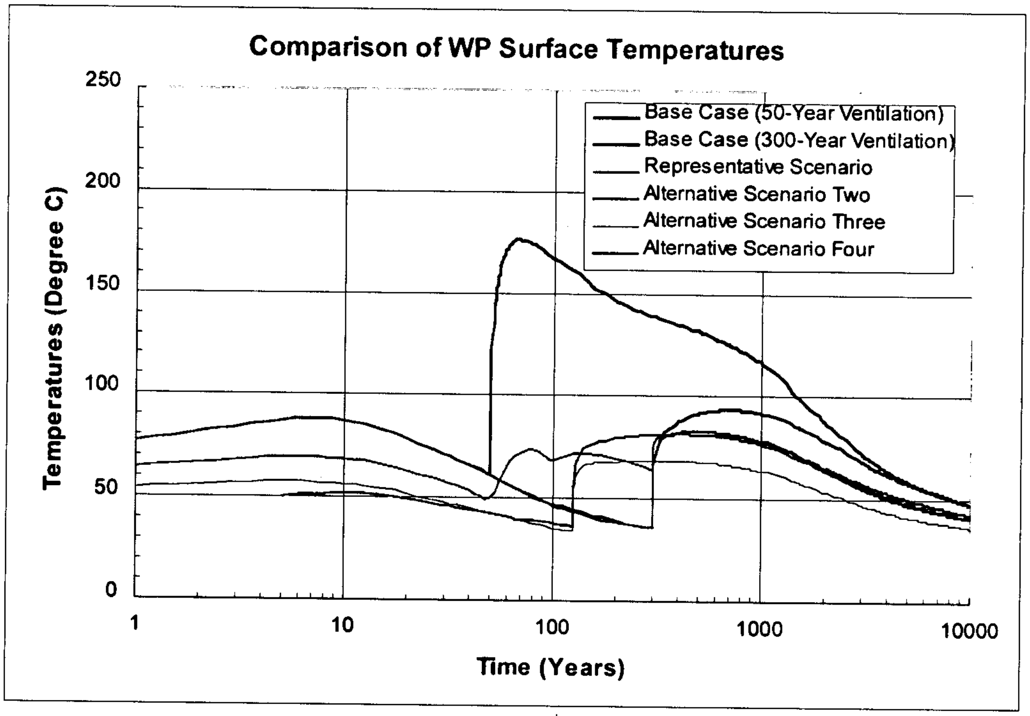


Figure 6-5. Waste Package Surface Peak Temperature Comparison by Scenario

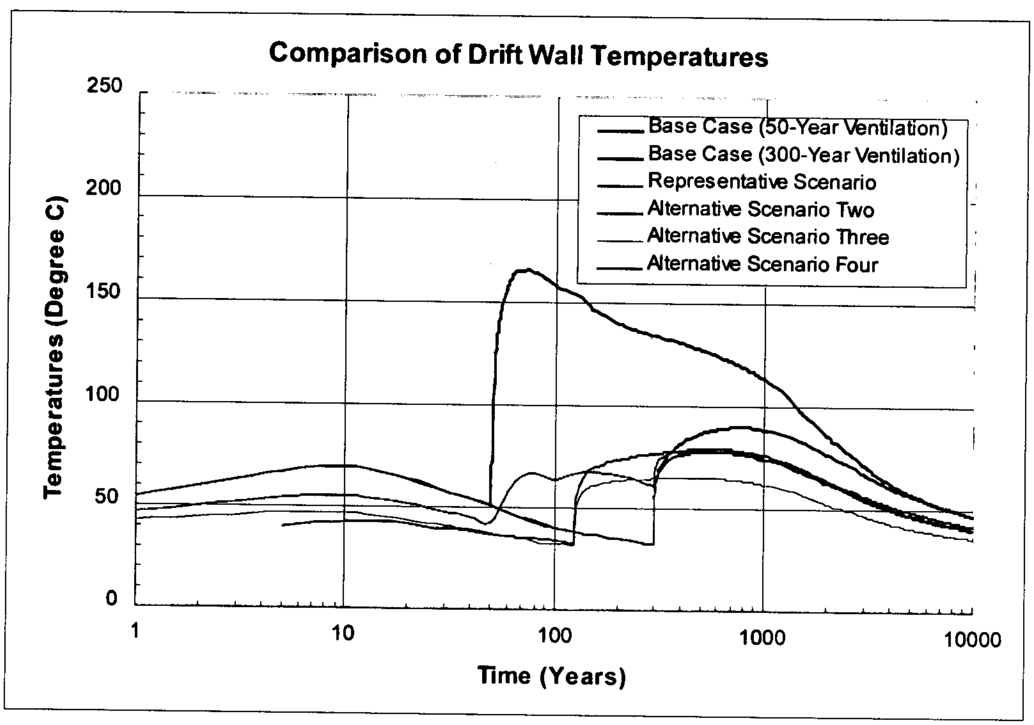


Figure 6-6. Drift Wall Peak Temperature Comparison by Scenario

6.3.3 The Base Case Repository

The *Base Case* repository has a thermal load of 1.45 kW/m with the emplacement drifts spaced at 81 meters apart. The ventilation rate is 15 m^3/sec and is calculated for periods of 25, 50, 100, 200, and 300 years (from Table 6-6). The peak temperature values for the 50 year ventilation case and the 300 year case are noted since they represent the minimum duration for ventilation and the maximum duration for the ventilation period, respectively, as described by this analysis. (The 25 year, 100 year and 200 year values are provided for reference only.)

For the case of 50 years of ventilation, the following peak temperatures occur:

- The waste package peak temperature reaches 176°C. This is greater than the maximum allowable low end point temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature reaches 165° C. This is greater than the maximum allowable temperature of 96°C during preclosure, but is less than the 200°C threshold (Section 4.2.3).
- The middle-of-the-pillar peak temperature reaches 95°C which allows free drainage between the emplacement drifts and satisfies the high end point of the thermal range criteria (Section 4.2.2). However, this is close to the temperature that places the rock in a boiling environment and further investigation is warranted to determine the width of the non-boiling environment in the rock.

For the case of 300 years of ventilation, the following peak temperatures occur:

- At 300 years of ventilation, the waste package peak temperature reaches 93°C. This is greater than the maximum allowable temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature reaches 90°C. This is less than the maximum allowable temperature of 96°C during preclosure and 200°C at any time (Section 4.2.3).
- The PTn formation peak temperature is 45°C. This is less than the maximum allowable temperature of 90°C (Section 4.2.1).
- The zeolite formation temperature is 49°C. This is less than the maximum allowable temperature of 70°C (Section 4.2.1).
- At 300 years of ventilation, the middle-of-the-pillar peak temperature reaches 74°C which allows free drainage between the emplacement drifts and satisfies the high end point of the thermal range criteria (Section 4.2.2).

6.3.4 Representative Scenario

The *Representative Scenario* repository operates at a 1.0 kW/m thermal load (either accomplished with an average waste package spacing determined from the waste inventory comprised of the design capacity waste packages or, a larger number of smaller capacity waste packages at an average minimum spacing of 10 cm). The emplacement drift are spaced at 81 meters apart and the preclosure period is 300 years. The ventilation duration and rate are 50 years at 15 m^3/sec, followed by 50 years at 3.0 m^3/sec which is followed by 200 years at 1.5 m^3/sec.

The 2D ANSYS modeling produced the following results (from Table 6-6):

- The waste package surface peak temperature is 83°C. This is less than the maximum allowable temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature is 79°C. This is less than the maximum allowable temperature of 96°C during preclosure and 200°C at any time (Section 4.2.3).
- The PTn formation peak temperature is 41°C. This is less than the maximum allowable temperature of 70°C (Section 4.2.1).
- The zeolite formation temperature is 45°C. This is less than the maximum allowable temperature of 90°C (Section 4.2.1).
- Free drainage between the emplacement drift (Section 4.2.2) is satisfied since the peak temperature at the drift wall shows that the rock is not in a boiling environment.

6.3.5 Alternative Scenario Two (Increased Drift Spacing)

In *Alternative Scenario Two*, the repository is subjected to a 1.45 kW/m thermal load which results from an average waste package spacing of 0.1 meters. The emplacement drift spacing is 120 meters and the repository is ventilated at 15 m^3/sec for 300 years. The following results are generated by the 2D ANSYS modeling (from Table 6-6):

- The waste package surface peak temperature is 87°C. This is higher than the maximum allowable temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature is 78°C. This is less than the maximum allowable temperature of 96°C during preclosure and 200°C at any time (Section 4.2.3).
- The PTn formation peak temperature is 38° C. This is less than the maximum allowable temperature of 70°C (Section 4.2.1).
- The zeolite formation temperature is 42°C. This is less than the maximum allowable temperature of 90°C (Section 4.2.1).
- Free drainage between the emplacement drift (Section 4.2.2) is satisfied since the peak temperature at the drift wall shows that the rock is not in a boiling environment.

6.3.6 Alternative Scenario Three (Increased Waste Package Spacing)

In *Alternative Scenario Three* the repository is subjected to a 0.7 kW/m thermal load which is a function of an average waste package spacing of 5.0 meters. The emplacement drift spacing is 81 meters and the repository is ventilated at 15 m^3/sec for 125 years. The following results are generated by the 2D ANSYS modeling (from Table 6-6):

- The waste package surface peak temperature is 69°C. This is less than the maximum allowable temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature is 65°C. This is less than the maximum allowable temperature of 96°C during preclosure and 200°C at any time (Section 4.2.3).
- The PTn formation peak temperature is 36°C. This is less than the maximum allowable temperature of 70°C (Section 4.2.1).
- The zeolite formation temperature is 41°C. This is less than the maximum allowable temperature of 90°C (Section 4.2.1).
- Free drainage between the emplacement drift (Section 4.2.2) is satisfied since the peak temperature at the drift wall shows that the rock is not in a boiling environment.

6.3.7 Alternative Scenario Four (Aging the Waste Packages)

In *Alternative Scenario Four* the repository is subjected to an approximately 0.6 kW/m thermal load that is a function of aging the waste packages for a period of 30 years prior to emplacement. The average waste package spacing is calculated at 2.0 meters. The emplacement drift spacing is 81 meters and the repository is ventilated at 15 m^3/sec for 125 years. The following results are generated by the 2D ANSYS modeling (from Table 6-6):

- The waste package surface peak temperature is 82°C. This is less than the maximum allowable temperature of 85°C (Section 4.2.2).
- The drift wall peak temperature is 78°C which is less than the maximum allowable peak temperature of 96°C during preclosure and 200°C at any time (Section 4.2.3).
- The PTn formation peak temperature is 40°C. This is less than the maximum allowable temperature of 70°C (Section 4.2.1).
- The zeolite formation temperature is 45°C. This is less than the maximum allowable temperature of 90°C (Section 4.2.1).
- Free drainage between the emplacement drift (Section 4.2.2) is satisfied since the peak temperature at the drift wall shows that the rock is not in a boiling environment.

6.3.8 Soil Surface Temperature Limitation

The *Yucca Mountain Site Characterization Project Requirements Document* (YMP 2001b, 1.3.2.F, p. 1.3-12) states that "The MGR shall limit the change in temperature, at 45 cm below the soil surface, to 2°C above what the established naturally occurring pre-emplacement average annual surface temperature is within the footprint (see footnote a) of the MGR." (Section 4.2.10).

(footnote a) The MGR footprint is defined as that area directly above emplaced waste packages and extending 500 m horizontally beyond the edge of emplaced packages.

The soil surface temperature is strongly affected by the model boundary conditions and cannot be properly judged by the model described in this analysis. The boundary conditions are user defined, therefore it would not be fair to make an assessment on satisfying this criteria based on the modeling approach used in this analysis

To properly consider the requirement would necessitate the construction of a different model which is beyond the scope of this analysis and can be evaluated in future work.

6.4 REPOSITORY SCENARIO SUMMARY AND DISCUSSION

6.4.1 Comparison Between the Base Case and Representative Scenario Repository

Examination of the peak temperature values in Table 6-6 for the *Base Case* (1.45 kW/m) and *Representative Scenario* (1.0 kW/m) shows that the lower temperature repository develops lower peak temperatures for the Waste Package Surface and the Drift Wall in all the comparable categories. The peak temperature values experienced in the PTn and the zeolite formations are approximately the same. For the *Base Case*, Table 6-6 shows that the peak temperature values become successively less with an increased ventilation period, but occur later during the residency, as the ventilation duration is extended out in the increments of 25, 50, 100, 200, and

300 years (Section 6.2.3.2). At 300 years of ventilation the *Base Case* satisfies the Drift Wall criteria, but it falls short of satisfying the Waste Package criteria. The *Representative Scenario* repository satisfies the thermal criteria.

6.4.2 Representative Scenario Repository Sensitivity Analysis Results

The *Representative Scenario* repository (1.0 kW/m) is compared to three variations in a sensitivity analysis to determine the impact of altering major variables that define the repository thermal environment.

Alternative Scenario Two is a global comparison which serves to compare the *Representative Scenario* case with a repository that has the same areal mass load but has a line load that is the same as the *Base Case* higher temperature operating mode repository. For example, a unit length of emplacement drift for the *Representative Scenario* repository has an area of influence of 81 m^2, hence an areal mass thermal load of 0.012 kW/ m^2. In *Alternative Scenario Two* the emplacement drift spacing is increased to 120 meters and the thermal load applied is 1.45 kW/m. Therefore, a unit length of emplacement drift has an area of influence of 120 m^2. This is also equivalent to a 0.012 kW/m^2 areal mass thermal load. Both repositories are subject to 300 years of ventilation, however *Alternative Scenario Three* is at 15 m^3/sec for the whole duration.

It has been determined that the *Representative Scenario* repository will satisfy the thermal criteria. Comparatively, for *Alternative Scenario Two*, Table 6-6 shows that the peak temperature for the Waste Package Surface is about 87°C, which exceeds the Waste Package thermal criteria. Otherwise, there is no significant variance in the peak values in the other comparable categories. It should be noted that this temperature occurs during preclosure and that it is the only peak temperature value in the sensitivity analysis that happens in the preclosure period. All the other peak temperature values occur during postclosure.

Comparing the *Representative Scenario* repository to the impact of increasing the waste package spacing (hence reducing the thermal load on the repository to 0.7 kW/m) and lengthening the forced ventilation period to 125 years at 15 m^3/sec, as is the case for *Alternative Scenario Three,* shows significantly reduced peak temperature values for the Waste Package Surface and the Drift Wall, on the order of 14°C lower (refer to Table 6-6). These values also occur earlier during the residency. There is only a marginal decrease in the PTn and zeolite formation peak temperature values in *Alternative Scenario Three.*

The last comparison, *Alternative Scenario Four,* looks at the effect of 30 years of aging on the waste inventory while maintaining the waste package spacing at approximately the same as for the *Representative Scenario* repository and having 15 m^3/sec, forced ventilation for 125 years. The peak temperature values, for both scenarios, are not more than 1°C different in all the comparable categories. This can be attributed to Newton's law of cooling (Section 6.1.2, Equation 6-2). It can be seen that the lower temperature gradient, T_w - T_a (from Equation 6-2), for *Alternative Scenario Four* leads to a lower heat flow rate. As a result the utilization of the ventilation system for heat removal becomes less efficient and this promotes higher temperatures.

6.5 PARAMETER SENSITIVITY SUMMARY

6.5.1 Increased Emplacement Drift Split Length

The 600 meter split drift length (Section 4.2.9) was extended by two increments of 100 meters. The peak temperatures reached in the increased split drift length with a 1.0 kW/m thermal load are examined in order to determine the range that a split drift length would reside, while accommodating the peak temperature criteria of 85°C for the waste package surface (Section 4.2.2). The effect of increasing the length of the emplacement drift into the range of 600 to 700 meters and 700 to 800 meters (Section 5.5) was considered and the results are presented in Table 6-7. Refer to Figure III-4 and Figure III-5 from Attachment III, for the temperature curves for the Drift Wall and the Waste Package Surface, respectively. The Air Temperatures are obtained from Table III-2 in Attachment III. The peak temperature for the waste package and the drift wall occur during postclosure, i.e., after 300 years. The emplacement drift air peak temperature values occur in the pre-closure period.

Table 6-7. Effect of Increased Emplacement Drift Split Length on Peak Temperature

2D Simulation	Parameter	1.0 kW/m Ventilation: 0-50 @ 15m^3/s, 50-100 @ 3 m^3/s, 100-300 @ 1.5 m^3/s		
		500-600 m	**600-700 m**	**700-800m**
WP Surface Temperature	°C	83	84	86
	Year	483	463	448
Drift Wall Temperature	°C	79	81	82
	Year	548	528	488
Air *Temperature*	°C	67	71	75
	Year	*150*	*150*	*150*

Examining the Waste Package surface temperature with respect to the three lengths of airflow travel, 500-600 meters, 600-700 meters and 700-800 meters, shows that the peak temperature increases as the length of emplacement drift is increased. Similarly, there is a small increase in the Drift Wall temperature and the Air temperature as the length of emplacement drift is increased.

6.5.2 Tptpll Rock Unit Thermal Conductivity

In this analysis the most recent thermal conductivity values for the Tptpll unit are used. The values are 1.76 W/m·K and 1.22 W/m·K for temperatures ≤ 100°C and > 100°C, respectively (Section 5.7.4). In order to determine the impact of these most recent thermal conductivity values, the resulting peak temperature values are compared to the peak temperature values using the superceded thermal conductivity values for this rock unit. The previous set of thermal conductivity values for the Tptpll are 2.02 W/m·K and 1.20 W/m·K for temperatures ≤ 100°C and > 100°C, respectively (Section 5.7.4). In Attachment VIII, Figure VIII-4 for the Drift Wall Temperatures and Figure VIII-5 for the Waste Package Temperatures illustrate the temperature curves that are generated using the different thermal conductivity's in the modeling. The effects on the Waste Package temperature and the emplacement Drift Wall are shown in Table 6-8. Note that the change in the peak temperature values is 2°C.

Table 6-8. Two-Dimensional Model Thermal Conductivity Comparison

Attachment VIII			Thermal Load 1.0 kW/m, Drift Spacing 81 m			
			Waste Package		Drift Wall	
Vent (yrs)	Rate (m^3/s)	Parameter	Lower *k*	Higher *k*	Lower *k*	Higher *k*
Postclosure	N/A	°C	83	*81*	79	*77*
		Year	483	*528*	548	*568*

Note: k = thermal conductivity

6.5.3 6-Segment Drift Results Compared to the 9-Segment Drift Results

The emplacement drift used in the calculations is 600 meters long and is divided into six segments of equal length (Section 6.2.3.1). The effect of increasing the number of segments in the 600 meter length by 50%, to nine, with various segment lengths is investigated (Section 6.2.3.1). In Attachment VII, Figure VII-4 and Figure VII-5 show the Drift Wall Temperatures and the Waste Package Temperatures, respectively. Table 6-9 shows the comparison on the Waste Package peak temperature values and the Drift Wall peak temperature values. The table illustrates that there is little impact to the results.

Table 6-9. Peak Temperature Comparison of the 6-Segment and 9-Segment Drift Model

Attachment VII			Thermal Load 1.0 kW/m, Drift Spacing 81 m			
Parameter			Waste Package		Drift Wall	
Vent (yrs)	Rate (m^3/s)	**Segments**	6	*9*	6	9
Postclosure	N/A	°C	82.8	*82.7*	79.3	*79.2*
		Year	483	*483*	548	*548*

Note: For the 6-segment drift the peak temperature values correspond to those found in Table 6-7 and Table 6-8 without round off.

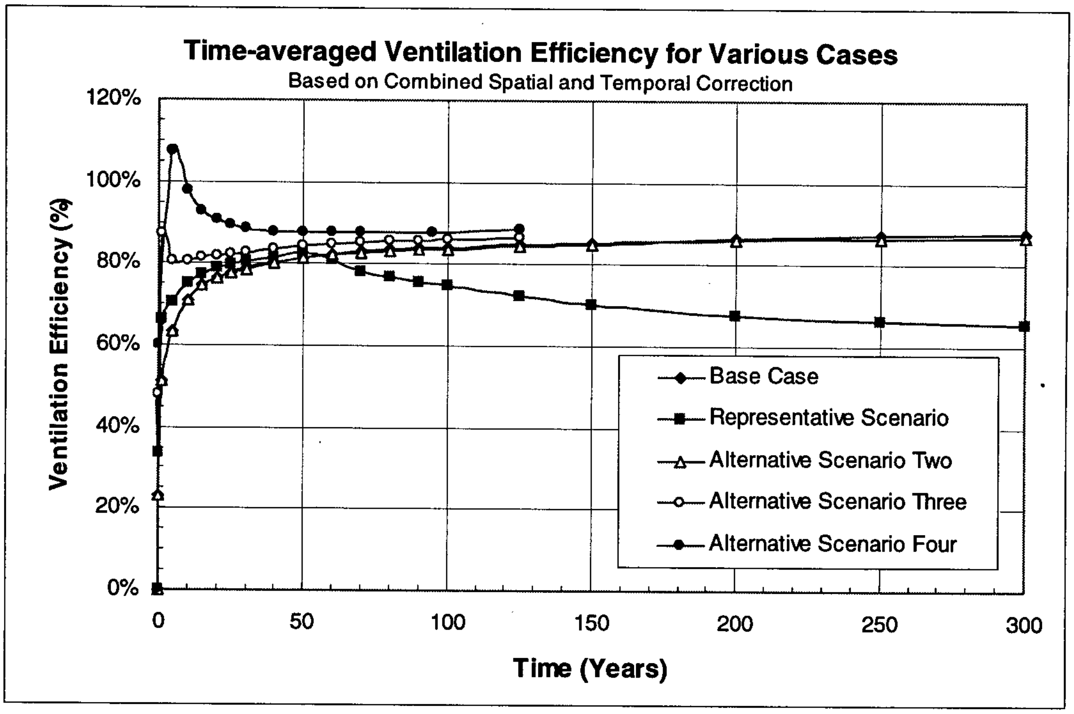
6.5.4 Ventilation Efficiency

Ventilation efficiency is defined as the ratio of the heat removed by the ventilation airflow to the heat generated by the waste packages. The ventilation efficiency can be described by several different approaches. In this analysis the time-dependent or instantaneous ventilation efficiency and time-averaged or cumulative ventilation efficiency are discussed. The time-averaged ventilation efficiency curve is developed by dividing the cumulative heat removal rate value by the cumulative heat generation rate value for each of the time increments for the ventilation duration period. The time-dependent ventilation efficiency curve is developed by dividing the heat removal value by the heat generated value at each of the time increments for the ventilation duration period. Also, in calculating a ventilation efficiency either a spatial correction or a combined spatial and temporal correction is applicable. Only in the case of the *Representative Scenario* are these two separate corrections used. In addition to the ventilation efficiency calculated based on the combined spatial and temporal correction, a ventilation efficiency is calculated based on a spatial correction alone. This latter ventilation efficiency is calculated for use in the 3D analysis only.

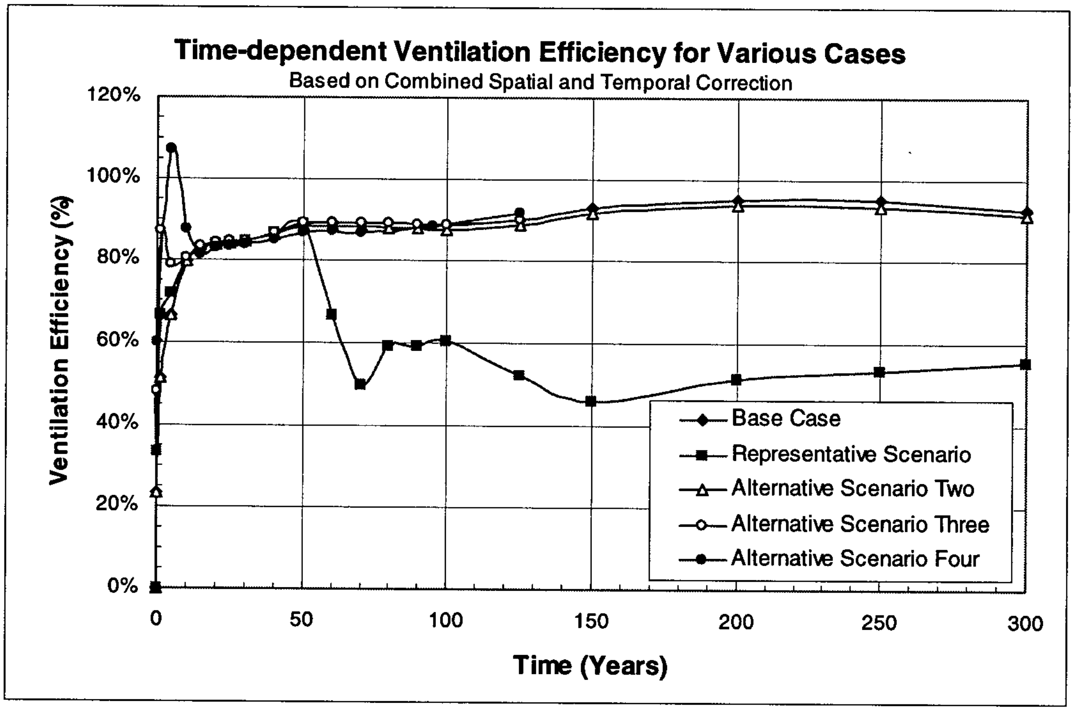
6.5.4.1 Time-averaged and Time-dependent Ventilation Efficiency

Two approaches are used to describe the ventilation efficiency for the *Base Case*, the *Representative Scenario*, and *Alternative Scenario Two, Three* and *Four*. One approach is the Time-averaged Ventilation Efficiency which is based on the combined correction for both spatial and temporal adjustment to the heat removal rate as discussed in the last part of Section 6.2.3.1. This is shown in Figure 6-7 (a) for the aforementioned scenarios. The other approach is the Time-dependent Ventilation Efficiency which is also based on the combined correction for the heat removal rate. This is shown in Figure 6-7 (b) for the aforementioned scenarios.

The time-averaged curves in Figure 6-7 (a) for the scenarios that maintain a constant forced ventilation rate are coincident. The *Representative Scenario* exhibits this trace for the period of forced ventilation. Then, as the natural ventilation is applied, the ventilation efficiency drops off accordingly. The anomalous curve is *Alternative Scenario Four* (30 years aging). The high efficiency spike in the curve is not physical, but a product of the methodology. This overestimation may be caused by combining the assumption of an initial waste package surface temperature of 70°C and the relatively low heat decay values due to the 30 years of aging the waste. Inspecting Table VI-5 shows that the values under "Heat Generated per 600 m" is less than those under the "Heat Removed per 600m" for the initial five years and does not become larger until year 10. From that point forward the curve resembles the other fixed ventilation scenario curves. A similar pattern is exhibited for the time-dependent curves in Figure 6-7 (b). The curves are less streamlined since the efficiency values are not cumulative.



(a)



(b)

Figure 6-7. Time-averaged and Time-dependent Ventilation Efficiencies for Various Cases: (a) Time-averaged; (b) Time-dependent

6.5.4.2 Application of the Ventilation Efficiency for the Representative Scenario

As identified in the Section 6.5.4 introduction, the *Representative Scenario* makes use of two separate ventilation efficiency calculations. The first ventilation efficiency derivation, found in Attachment III, Table III-5, utilizes only the spatial correction for the heat removal rate. The ventilation efficiency values are 74% of the total heat removed during the initial 50 years of the repository operation, 47% of the total heat removed during years 50 to 100, and 44% of the total heat removed during the years 100 to 300. This time frame determination corresponds to the duration of the 15 m^3/s forced ventilation period and the 3 m^3/s and 1.5 m^3/s natural ventilation periods for the repository. These ventilation efficiency values can be considered analogous to a flat rate applied over the reference time frame. The calculation is simply the sum of the heat removed during the reference time frame divided by the sum of the heat generated during the reference time frame. These are the ventilation efficiency values that are applied to the 3D model which is discussed in Section 6.2.3.5.

The second ventilation efficiency calculation presented in the *Representative Scenario*, is located in Table III-7. This ventilation efficiency is based on a combined spatial and temporal correction applied to the heat removal rates. Referring to Table III-7, the ventilation efficiencies are: 83%, 59% and 52%, respectively for the reference time frame and the applicable ventilation flowrate. This approach applies to the ventilation efficiency values found in Tables II-5, IV-5, V-5, VI-5, VII-5, and VIII-5. The ventilation efficiency figures are discussed in Section 6.5.4.3.

6.5.4.3 Ventilation Efficiency Curves

Using the *Representative Scenario* in Attachment III as an example, the first ventilation efficiency figure shown is the "*Average Heat Removal Rates at Different Drift Segments for Representative Scenario*", Figure III-7. This set of curves illustrates the percent heat removal for each of the reference time frames (50, 100 and 300 years) for each of the modeled segments. The second ventilation efficiency figure shown is the "*Overall Heat Generation and Removal Rates at Different Time for Representative Scenario*", Figure III-8. This figure is expressed as the power decay during the reference time frame. The two curves in this figure represent the heat generation rate and the heat removal rate for the 300 year ventilation duration period. The third ventilation efficiency graph, "*Time-averaged and Time-dependent Ventilation Efficiencies for Representative Scenario*", Figure III-9, depicts two curves derived from the power decay curves (Figure III-8) expressed as percentage values. One is the time-averaged ventilation efficiency curve and the other is the time-dependent ventilation efficiency curve. Both of these curves are plotted for the ventilation duration period of 300 years.

The above approach for the ventilation efficiency figures applies to the ventilation efficiency curves found in Attachments II, IV, V, VI, VII, and VIII. Note that all the models have six segments except in Attachment VII, where, as part of the sensitivity study, the model has nine segments.

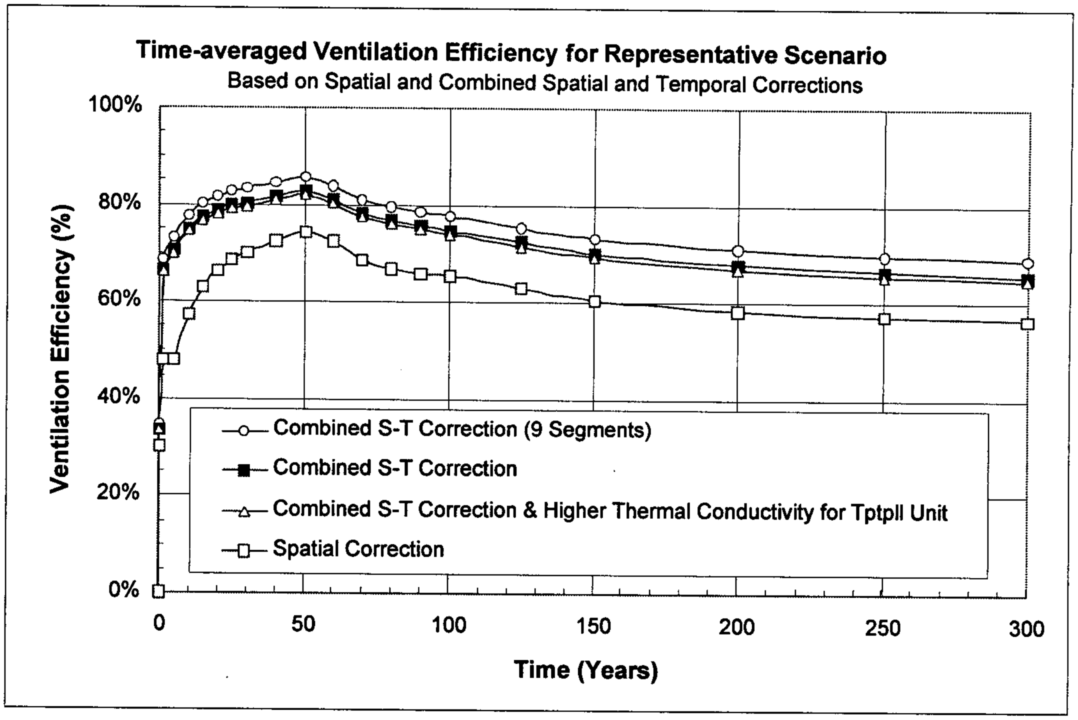
6.5.4.4 Representative Scenario Ventilation Efficiency for Sensitivity Study

The *Representative Scenario* heat generation and heat removal rates are used in a sensitivity study to illustrate the ventilation efficiencies for various cases. Figure 6-8 (a) and (b) show the time-averaged and the time-dependent curves, respectively, for each of the cases.

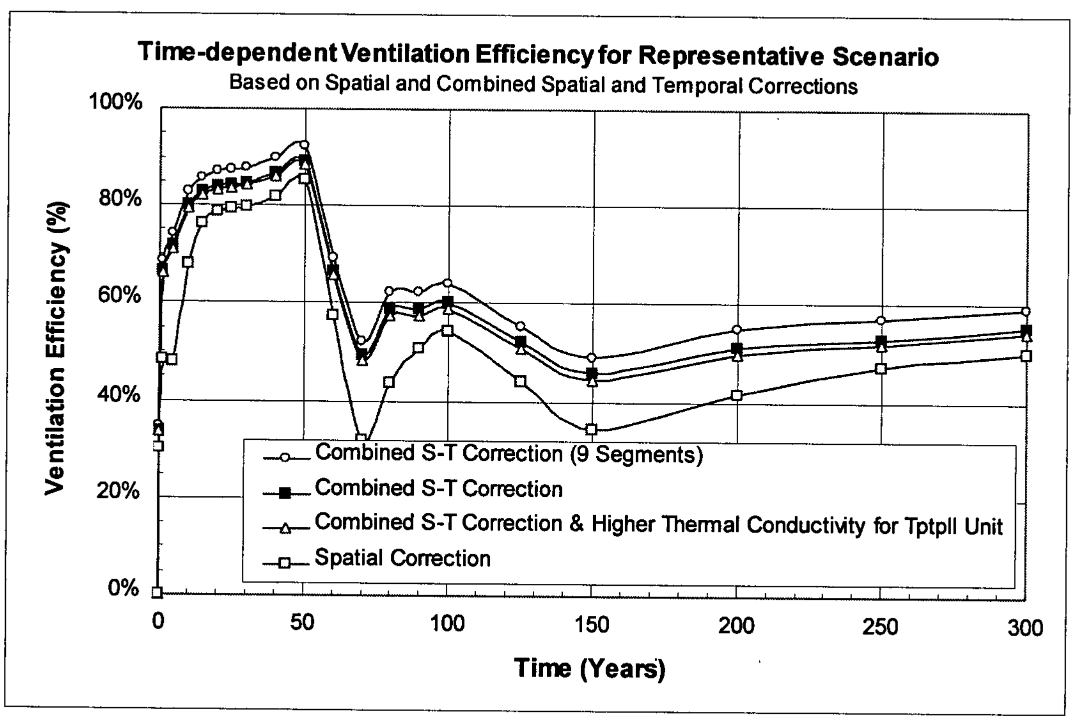
It can be seen that the ventilation efficiencies estimations based on applying a spatial correction only are lower than those predicted by the application of the combined spatial and temporal correction to the heat removal rate. Therefore the spatial correction is considered conservative. This is illustrated by the Spatial Correction curve being lower than the spatial and temporal ventilation efficiency curves. The spatial efficiency curve is applied in the 3D model to be conservative.

The combined spatial and temporal correction is considered to be the more representative approach since this combined correction takes into account both the axial variation of the air temperature and the variation of the air temperature with respect to time (refer to discussion in Section 6.2.3.1). Therefore it has been applied to the other cases that have been analyzed.

In Figure 6-8 the Combined S-T Correction (9 Segment) curve shows that as the drift segment in the model is reduced in size by using the 9-segment model (refer to Section 6.5.3) there is a corresponding increase in the predicted ventilation efficiency. Therefore, the 6-segment drift model can be considered as the conservative approach to the modeling. Further investigation into the sensitivity of the drift segment size on temperature and ventilation efficiency prediction and the validity of the ventilation model used for this analysis can be considered in a future evaluation.



(a)



(b)

Figure 6-8. Comparison of Time-averaged and Time-dependent Ventilation Efficiencies for the Representative Scenario: (a) Time-averaged; (b) Time-dependent

6.6 THREE-DIMENSIONAL 1.0 kW/M MODEL

To evaluate the variation of temperatures in the emplacement drift axial direction a three-dimensional analysis is performed. This is represented by the simple three-waste-package system 3D model, shown in Figure 6-2 and it is only applicable to this analysis. Section 6.2.1.2 describes the configuration for this model. In this analysis, due to the limitation of the numerical approach, ventilation simulation relies only on two-dimensional models, while the simple three-waste-package system 3D model is used as part of sensitivity study.

6.6.1 Peak Temperature Values from the Three Dimensional Model

A three-dimensional model for the *Representative Scenario* repository was constructed (Figure 6-2) and the peak temperature values are shown in Table 6-10. Refer to Attachment IX, Figure IX-1 for the temperature curves at the springline and at the crown of the emplacement drift wall. Figure IX-5, shows the Waste Package Surface temperatures for individual 21-PWR, 44-BWR and the DHLW waste packages.

Table 6-10. Three-Dimensional Model Peak Temperatures

Attachment IX		1.0 kW/m		
		Springline		Crown
Drift Wall Temperature	°C	77		74
	Year	*65*		*67*
	WP type	21 PWR	44 BWR	DHLW
WP Surface Temperature	°C	81	78	77
	Year	*65*	*65*	*65*

The 3D model represents the *Representative Scenario* repository with a 1.0 kW/m thermal load (Figure 6-2). The following results are generated by the 3D ANSYS simulation (from Table 6-10):

- The waste package surface peak temperature for the 21-PWR waste package is 81°C; the 44-BWR waste package experiences 78°C and the DHLW waste package experiences 77°C. The peak temperature occurs on the bottom surface of the waste package.
- The drift wall peak temperature at the springline is 77°C and at the crown it is 74°C.

6.6.2 Axial Temperature Curves from the Three Dimensional Model

In Attachment IX, Figure IX-2, the drift wall temperature at the crown; IX-3, the drift wall temperature at the springline; IX-4, the temperature at the invert surface; and IX-6 the waste package bottom surface temperature are shown in an elevation view. The temperature profile for each of these figures is generated along the axial dimension of 21.89 meters used for the 3D model (Section 6.2.1.2, Table 6-1). The axial temperature curves are for the preclosure years 1, 50, 67 (the year the peak temperature occurs for the emplacement drift crown), 100 (natural ventilation goes to 1.5 m^3/sec) and 300 years (closure). Also shown is the year 544, during which the postclosure temperature peaks. The curves profile the temperature along the axial dimension of the 3D model (Figure 6-2). The peak temperature occurs at the bottom surface of the 21-PWR waste package.

The curves in Figure IX-6 can be related back to Figure 6-2 by recognizing that the origin in Figure IX-6 corresponds to the intersection point of the vertical axis and the *Centerline Emplacement Drift* from Figure 6-2. Relating Figure 6-2 to Figure IX-6, for the curve at 67 years (the peak temperature curve) in Figure IX-6 is interpreted as follows: 3.18 m to the right of the origin the temperature is slightly above 80°C. The temperature remains at about the same level for 5.17 m (the length of the 21-PWR waste package). The temperature cools to about 76°C moving along the next 3.18 m (the space between the 21-PWR and the DHLW package). The temperature remains about the same over the next 3.59 m (the length of the DHLW package) and the 0.1 m space. Continuing over the next 5.17 m (the length of the 44-BWR package) and an additional 1.5 m of spacing, the temperature increases to about 78°C.

6.7 THERMAL RESPONSE IN THE REPOSITORY LOWER BLOCK

This analysis is modeled as a representative 2D approximation using the straigraphic column located at the centroid of the primary block (Section 5.7.1). A qualitative description of the lower block waste emplacement inventory thermal effect to the PTn and the zeolite layer is presented in the following discussion.

The coordinates of the lower block centriod are N233510, E172093 and the invert elevation is 988.60 meters at this location (Section 5.7.3). The topographic elevation (surface) is 1233.0 meters (Section 5.7.4). The Tpcpv3 unit represents the start of the rock formation at elevation 1196.0 meters (Section 5.7.4). Therefore the overburden is 37.0 meters thick. Table 6-11 shows the corresponding elevation for each of the lower block stratigraphic units.

Comparing the stratigraphic column for the primary block (Section 5.7.2, Table 5-3) to that of the lower block (Section 5.7.4, Table 5-3a) it can be observed that all the stratigraphic units present in the primary block stratigraphic column are present in the lower block stratigraphic column. In general, the stratigraphic units in the lower block stratigraphic column are of similar thickness to that of the stratigraphic units found in the primary block stratigraphic column. Where significant differences in the thickness occur, such as in the Calico formation, the thickness is larger in the lower block stratigraphic column. The Calico formation is the host formation for the zeolites and in the lower block stratigraphic column this formation is more than twice as thick as it is in the primary block stratigraphic column.

The distance from the primary block invert elevation to the base of the PTn unit and to the top of the Calico formation are approximately 207 meters and 129 meters, respectively (Section 6.2.3.6, Table 6-4). In the lower block stratigraphic column these dimensions are approximately 170 and 182 meters, respectively.

In the *Representative Scenario* the peak temperatures for the primary block PTn and the zeolite (Calico) units are 41°C and 45°C, respectively (Section 6.3.2, Table 6-6). Since the lower block PTn layer would be in closer proximity to the emplacement horizon, the peak temperature it would experience is likely to be higher than the primary block PTn peak temperature value. Nevertheless, the peak temperature probably would not exceed the thermal criteria value of 70°C (Section 4.2.1) since the intervening stratigraphic column is still reasonably thick at greater than 170 meters. Conversely, the lower block zeolite layer is farther away from the emplacement horizon than the primary block zeolite unit, therefore, it can be expected that the peak temperature will be less than what is experienced in the primary block zeolite thereby the thermal criteria of 90°C (Section 4.2.1) will be satisfied.

Therefore, it can be rationalized that the thermal response in the lower block stratigraphic column will be similar to that of the thermal response demonstrated in Section 6.3 for the primary block stratigraphic column. However, since ANSYS computational runs have not been performed for the lower block stratigraphic column further investigation will be necessary in future analyses.

Table 6-11. Thickness and Elevation of Lower Block Stratigraphic Units

T/M Unit	Stratigraphic Unit	Thickness (m)	Elevation (m) (top of Stratigraphic Unit)
N/A	Overburden	37.0	1233.0
TCw	Tpcpv3	0.0	1196.0
PTn	Tpcpv2	3.2	1196.0
	Tpcpv1	3.1	1192.8
	Tpbt4	1.5	1189.7
	Tpy	4.6	1188.2
	Tpbt3	5.3	1183.6
	Tpp	7.0	1178.3
	Tpbt2	8.5	1171.3
	Tptrv3	2.4	1162.8
	Tptrv2	1.5	1160.4
TSw1	Tptrv1	0.2	1158.9
	Tptrn	49.6	1158.7
	Tptrl	6.9	1109.1
	Tptpul	80.3	1102.2
TSw2	Tptpmn	30.2	1021.9
	Tptpll	105.3	991.7
	Tptpln	52.2	886.4
TSw3	Tptpv3	10.0	834.2
CHn1	Tptpv2	3.8	824.2
	Tptpv1	12.3	820.4
	Tpbt1	1.1	808.1
	Calico	114.1	807.0
CHn2	Calicobt	15.2	692.9

Source: Section 5.7.4

7. CONCLUSIONS

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the technical input information quality may be confirmed by review of the DIRS database (AP-3.15Q, Rev 2, ICN 1, Section 5.4.1(e), p. 11).

7.1 LOWER TEMPERATURE REPOSITORY

7.1.1 Representative Scenario Repository

The *Representative Scenario* repository does not place the emplacement drift rock into a boiling environment which is demonstrated by the peak temperature values not exceeding 96°C. Most importantly, the *Representative Scenario* repository does not exceed the waste package temperature constraint of 85°C. PTn and zeolite temperature criteria are not exceeded in the *Representative Scenario* repository (refer to Section 6.3.5). It should be noted that the measure for thermal compliance for the PTn and the zeolite formations is a function of the stratigraphic column and the associated peak temperature values which may vary depending on stratigraphic layer thickness throughout the repository footprint. If the waste package spacing is increased from the 10 cm spacing of the *Base Case* repository or, if the waste package capacity is reduced to achieve the 1.0 kW/m thermal load, the total emplacement drift excavation length will increase with a corresponding increase in the repository cost.

7.1.2 Base Case Repository

When the *Base Case* repository (1.45 kW/m) is subjected to 15 m^3/sec forced ventilation for up to 50 years it cannot satisfy the thermal criteria. The *Base Case* repository can achieve the non-boiling condition for the emplacement drift rock by extending the duration of the ventilation period out towards the 300 year range. Nevertheless, it still will not satisfy the waste package thermal criteria and exceeds 85°C at the waste package surface by 8°C (refer to Section 6.3.4).

7.1.3 Representative Scenario Repository Vs Alternative Scenario Two

Increasing the emplacement drift spacing reduces the drift wall peak temperature by 1°C compared to that of the *Representative Scenario* repository. However, the waste package peak temperature is 4°C higher than occurs in the *Representative Scenario* repository and exceeds the thermal criterion by 2°C (refer to Sections 6.3.6 and 6.4.2). The peak drift wall temperature value for *Alternative Scenario Two* is achieved with forced ventilation for 300 years. Additionally, the impact to the PTn and the Zeolite formations show a 3°C lowering of the peak temperature.

7.1.4 Representative Scenario Repository Vs Alternative Scenario Three

Reducing the thermal line load to 0.7 kW/m from 1.0 kW/m (by increasing the waste package spacing) shows a trend to reduce the repository peak temperatures for both the waste package surface and the drift wall, however the ventilation strategies are different (refer to Sections 6.3.7 and 6.4.2). The increased spacing between the waste packages will lead to more emplacement drift excavation with a corresponding increase in the cost.

7.1.5 Representative Scenario Repository Vs Alternative Scenario Four

Aging the waste package will reduce the repository peak temperatures by 1°C for both the waste package surface and the drift wall compared to the *Representative Scenario* repository. This appears to be a small advantage and further study would be required to prove aging as a feasible alternative to achieve the lower temperature goals (Refer to Sections 6.3.8 and 6.4.2).

7.1.6 Impact of Increased Emplacement Drift Split Length

Increasing the emplacement drift split length in the model demonstrates that the peak temperature will increase for the waste package surface, the drift wall, and the air (Section 6.5.1). In the 600 to 700 meter length, the waste package peak temperature is 84°C. In the range 700 to 800 meters, the peak temperature for the waste package surface is 86°C. Therefore, it can be concluded, based on these nominal results, that the cutoff length for the emplacement drift split length is 700 meters before the temperature exceeds the waste package surface constraint of 85°C. The air temperature is for reference only.

7.1.7 Sensitivity to Tptpll Thermal Conductivity

The effect of using the most recent Tptpll thermal conductivity value in the model on the peak temperature is minimal and conservative. The peak temperature increases by 2°C for both the waste package surface and the drift wall when the most recent thermal conductivity value is used in the modeling (Section 6.5.2).

7.1.8 Sensitivity to Drift Segments

Increasing the number of segments in the 2D model from 6 to 9 has a minimal impact on the peak temperature. Peak temperatures for the waste package and the drift wall decrease by 0.1°C (Section 6.5.3). Therefore increasing the number of segments in the model is not necessary.

7.1.9 Three-Dimensional Model of the Representative Scenario Repository

The 3D ANSYS model is a simple three-package-system, specific to this analysis. It serves only to demonstrate the peak temperature distribution in the axial direction for the three-waste package model which is not attainable with the 2D model (Section 6.6). The elevation views in Attachment IX illustrate that there are no extreme temperature fluctuations over the individual waste packages along axial direction.

7.2 DEVELOPED DATA

This analysis has served to document the inputs found in Sections 4.1, 4.2, and 5. By using the inputs with qualified software (Section 3) and the methodology described in Section 6, output has been produced and submitted to the TDMS, in accordance with AP-SIII.3Q. The output file has been assigned DTN: MO0107MWDTEM05.011.

7.3 UNCERTAINTIES AND RESTRICTIONS

The conclusions drawn from this analysis are preliminary in nature since there are uncertainties associated with the input data, such as the thermal properties of the stratigraphic column, the invert material, the waste inventory and the assumptions presented in Section 5.

Therefore, outputs/conclusions from this analysis should not be used as input for documents supporting procurement, fabrication, or construction nor used in verified design unless further detailed studies are undertaken.

7.4 RECOMMENDATIONS

It should be noted that the measure for thermal compliance for the PTn and the zeolite formations is a function of the stratigraphic column and the associated peak temperature values may vary depending on stratigraphy throughout the repository footprint. Accordingly, since the focus of this analysis concentrated on the primary block design inventory emplaced at a representative stratigraphic location defined by the primary block centroid, additional study on the thermal environment at strategic locations throughout the primary block and the lower block (refer to Section 6.7 for discussion on the lower block thermal response) with the expanded waste inventory remains to be accomplished by future investigations.

The air properties used in this analysis are determined by an assumed fixed temperature. Future investigation will determine the effect of seasonal temperature variations on the intake ventilation air properties and the effect of the rock thermal response in the ventilation airways on the intake ventilation air properties. Additionally, further investigation is proposed to determine the design and application of the ventilation efficiency for both the two- and three-dimensional models presented in this analysis.

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9. ATTACHMENTS

ATTACHMENT I

CALCULATION OF HEAT DECAY PERCENTAGE VALUES AND VOLUMETRIC HEAT GENERATION RATES

This attachment presents the calculations of the heat decay percentage values with respect to the total initial heat output value for all CSNF waste packages and the volumetric heat generation rates used in this analysis.

The heat decay values in the form of volumetric heat generation rates for all 21-PWR waste packages are calculated for the initial linear heat loads of 1.0 and 1.45 kW/m. The following parameter values are used in the calculation:

Length of 21-PWR waste package:	5.165 m (Section 5.8.4)
Diameter of 21-PWR waste package:	1.564 m (Section 5.8.4)
Number of 21-PWR waste packages (absorber plates):	4,299 (Section 5.8.1)
Number of 21-PWR waste package (control rods):	95 (Section 5.8.1)
Number of 12-PWR waste package (long):	163 (Section 5.8.1)
Number of 44-BWR waste package (absorber plates):	2,831 (Section 5.8.1)
Number of 24-BWR waste package (thick absorber plates):	84 (Section 5.8.1)
Conversion factor:	3.1536×10^7 seconds/year

The conversion factor is used to convert the units from watts (joules/second) to joules/year, and is determined by taking 365 days for a year, 24 hours for a day, and 3,600 seconds for an hour as follows: 365 day/year × 24 hours/day × 3600 seconds/hour = 3.1536×10^7 seconds/year.

I-1 Heat Decay Percentage Values

The volumetric heat generation rates of waste packages are calculated based on weighted average heat decay percentages. The weighted average heat decay percentage for a given year is determined by dividing the total heat generated by all of the CSNF waste packages at that time by their total heat generated at the time of emplacement. For example, the total heat generated by all CSNF waste packages at the time of emplacement (see Table 5-5) is:

$$11.5284 \times 4299 + 3.1061 \times 95 + 9.5489 \times 163 + 7.3775 \times 2831 + 0.5206 \times 84 = 72{,}341.57 \text{ kW}$$

and the total heat generated by all CSNF waste packages at the time of 1 year after emplacement (see Table 5-5) is:

$$11.1460 \times 4299 + 3.0494 \times 95 + 9.2762 \times 163 + 7.1430 \times 2831 + 0.5105 \times 84 = 69{,}983.00 \text{ kW}$$

Thus, the average heat decay percentage with respect to the initial heat output at year 1 is:

$$\frac{\text{Total Heat at 1 Year}}{\text{Total Heat at 0 Year}} = \frac{69983.00}{72341.57} = 96.74 \quad \text{percent}$$

The average percentage values of the initial heat output at various time are given in Table I-1, Column 8.

Table I-1. Heat Generation Rates of Various Waste Packages

Time (years)	21-PWR Absorber Plates (kW/pk)	21-PWR Control Rods (kW/pk)	12-PWR Long (kW/pk)	44-BWR Absorber Plates (kW/pk)	24-BWR Absorber Plates (kW/pk)	Total Heat of All CSNF Waste Package (kW)	Decay Percentage with respect to Initial Total Heat
0.0	11.5284	3.1061	9.5489	7.3775	0.5206	72341.38	100.00%
0.5	11.3293	3.0767	9.4084	7.2556	0.5153	71114.35	98.30%
1.0	11.1460	3.0484	9.2762	7.1430	0.5105	69982.70	96.74%
5.0	10.0546	2.8403	8.4138	6.4667	0.4733	63212.88	87.38%
10.0	9.0735	2.6107	7.5931	5.8362	0.4322	57051.02	78.86%
15.0	8.2723	2.4104	6.9149	5.3126	0.3958	51991.92	71.87%
20.0	7.5827	2.2325	6.3290	4.8567	0.3636	47621.58	65.83%
25.0	6.9789	2.0735	5.8174	4.4515	0.3348	43777.90	60.52%
30.0	6.4443	1.9316	5.3636	4.0955	0.3094	40382.09	55.82%
35.0	5.9701	1.8043	4.9613	3.7783	0.2866	37365.90	51.65%
40.0	5.5493	1.6901	4.6044	3.4958	0.2662	34686.27	47.95%
45.0	5.1710	1.5878	4.2833	3.2437	0.2479	32283.00	44.63%
50.0	4.8334	1.4956	3.9971	3.0180	0.2318	30135.54	41.66%
60.0	4.2607	1.3385	3.5136	2.6352	0.2042	26493.88	36.62%
70.0	3.7974	1.2113	3.1214	2.3272	0.1822	23552.51	32.56%
80.0	3.4209	1.1078	2.8027	2.0786	0.1646	21166.76	29.26%
90.0	3.1133	1.0235	2.5426	1.8762	0.1505	19219.58	26.57%
100.0	2.8629	0.9545	2.3320	1.7125	0.1390	17638.22	24.38%
125.0	2.4836	0.8506	2.0125	1.4705	0.1226	15258.92	21.09%
150.0	2.1042	0.7468	1.6930	1.2285	0.1063	12879.61	17.80%
200.0	1.7415	0.6474	1.3897	1.0080	0.0926	10636.41	14.70%
300.0	1.3797	0.5435	1.0925	0.8004	0.0802	8433.59	11.66%
400.0	1.1659	0.4754	0.9188	0.6811	0.0722	7141.55	9.87%
500.0	1.0114	0.4225	0.7949	0.5949	0.0660	6207.19	8.58%
600.0	0.8908	0.3784	0.6985	0.5276	0.0607	5478.07	7.57%
700.0	0.7932	0.3421	0.6209	0.4734	0.0564	4888.59	6.76%
800.0	0.7119	0.3106	0.5566	0.4277	0.0526	4395.86	6.08%
900.0	0.6432	0.2843	0.5024	0.3894	0.0492	3980.68	5.50%
1000.0	0.5849	0.2619	0.4561	0.3564	0.0466	3626.37	5.01%
1500.0	0.3990	0.1892	0.3092	0.2517	0.0372	2499.31	3.45%
2000.0	0.3104	0.1539	0.2396	0.2011	0.0324	1959.99	2.71%
3000.0	0.2417	0.1262	0.1856	0.1606	0.0283	1538.40	2.13%
4000.0	0.2157	0.1149	0.1651	0.1439	0.0264	1374.53	1.90%
5000.0	0.1997	0.1075	0.1528	0.1324	0.0250	1270.70	1.76%
6000.0	0.1861	0.1014	0.1423	0.1232	0.0235	1183.46	1.64%
7000.0	0.1743	0.0958	0.1332	0.1148	0.0226	1107.13	1.53%
8000.0	0.1632	0.0907	0.1246	0.1074	0.0214	1036.12	1.43%
9000.0	0.1533	0.0859	0.1169	0.1008	0.0204	973.21	1.35%
10000.0	0.1441	0.0815	0.1098	0.0942	0.0194	913.15	1.26%

Note: Columns 1 through 6 are from Table 5-5.

I-2 Volumetric Heat Generation Rates for 2D Models

I-2.1 Base Case and Alternative Scenarios One and Two

The decay percentage values are used to determine the volumetric heat generation rates per waste package by multiplying the initial linear heat output value, such as 1.0 kW/m, by the decay percentage and then dividing by the volume of the 21-PWR waste package per linear meter. For example, at year 1 for an initial linear heat output of 1.0 kW/m, the volumetric heat generation rate is:

$$\frac{\text{Heat at 1 Year}}{\text{WP Volume}} = \frac{1.0 \times 0.9674}{\frac{1}{4} \times \pi \times 1.564^2} = 0.5036 \ \text{kW/m}^3$$

To convert the units from joule/second to joule/year, the above volumetric heat generation rate is multiplied by the conversion factor of 3.1536×10^7 seconds/year. Table I-1 lists the total heat generation rates of all of the CSNF waste packages and the calculated decay percentage with respect to the initial total heat output value of all CSNF waste packages. Table I-2 gives the volumetric heat generation rates for the initial linear heat output values of 1.0 and 1.45 kW/m.

I-2.2 Alternative Scenario Three

As stated in Section 5.3.1, *Alternative Scenario Three* considers an initial linear heat load of 0.7 kW/m. To analyze this case, the decay values of waste are obtained by multiplying those for *Alternative Scenario One* with a factor of 0.7, that is

$$P_{IV}(t) = 0.7 P_I(t) \qquad \text{(Eq. I-1)}$$

where P_{IV} = heat power of waste for *Alternative Scenario Three*, kW/m
P_I = heat power of waste for *Alternative Scenario One*, kW/m
t = time, year

For example, the volumetric heat generation rate at t=1 year for waste for *Alternative Scenario Three* is equal to 70 percent of that at 1 year for *Alternative Scenario One*, or

$$P_{IV}(1) = 0.7 P_I(1) = 1.11 \times 10^{10} \quad J / yr \cdot m^3$$

Table I-3 gives the volumetric heat generation rates for *Alternative Scenario Three.*

I-2.3 Alternative Scenario Four

As stated in Section 6.2.3.5, *Alternative Scenario Four* considers additional 30 years of waste aging. To analyze this case, the decay values of waste are set to be equal to those at 30 years older for other cases without additional waste aging, that is

$$P_{w/\ aging}(t) = P_{w/o\ aging}(t + 30) \qquad \text{(Eq. I-2)}$$

where $P_{w/\,aging}$ = heat power of waste with additional aging, kW/m
$P_{w/o\,aging}$ = heat power of waste without additional aging, kW/m
t = time, year

For example, the volumetric heat generation rate at t=5 years for waste with additional 30 years of aging is equal to that at 35 years for waste without additional aging, or

$$P_{w/\ aging}(5) = P_{w/o\ aging}(35) = 8.55\times10^{9} \quad J/yr\cdot m^{3}$$

Table I-4 gives the volumetric heat generation rates for waste with additional 30 years of aging.

I-3 Volumetric Heat Generation Rates for 3D Models

As stated in Section 6.2.3.5, ventilation is not explicitly simulated in 3D models. Its effects on temperatures are taken into account by reducing the heat decay values of waste packages during the preclosure period. The reduced heat decay values are calculated using the following expression:

$$P_{reduced}(t) = (1 - f_{ve})P_{regular}(t) \qquad \text{(Eq. I-3)}$$

where $P_{reduced}$ = reduced heat power of waste, kW/package
$P_{regular}$ = regular heat power of waste, kW/package
f_{ve} = average ventilation efficiency, percent
t = time, year

The ventilation efficiency for *Representative Scenario* is estimated based on 2D model, and presented in Attachment III. The average ventilation efficiencies over the ventilation periods of (0-50) years, (50-100) years, and (100-300) years are 74 percent, 47 percent, and 44 percent, respectively. With these ventilation efficiency values, the reduced heat power can be determined using the expression (I-3). For example, the volumetric heat generation rate at t=5 years for 21-PWR waste package is equal to

$$P_{reduced}(5) = (1-0.74)P_{regular}(5) = (1-0.74)\times3.20\times10^{10} = 8.31\times10^{9} \quad J/yr\cdot m^{3}$$

Table I-5 gives the volumetric heat generation rates for the 21-PWR, 44-BWR, and DHLW-Short waste packages.

Table I-2. Volumetric Heat Generation Rates for Linear Heat Loads of 1.0 and 1.45 kW/m

Time (years)	Decay Percentage with respect to Initial Total Heat	LL=1.0 kW/m (Representative Scenario) ($J/yr \cdot m^3$)	LL=1.45 kW/m (Base Case and Alternative Scenario Two) ($J/yr \cdot m^3$)
0.0	100.00%	1.64E+10	2.38E+10
0.5	98.30%	1.61E+10	2.34E+10
1.0	96.74%	1.59E+10	2.30E+10
5.0	87.38%	1.43E+10	2.08E+10
10.0	78.86%	1.29E+10	1.88E+10
15.0	71.87%	1.18E+10	1.71E+10
20.0	65.83%	1.08E+10	1.57E+10
25.0	60.52%	9.93E+09	1.44E+10
30.0	55.82%	9.16E+09	1.33E+10
35.0	51.65%	8.48E+09	1.23E+10
40.0	47.95%	7.87E+09	1.14E+10
45.0	44.63%	7.33E+09	1.06E+10
50.0	41.66%	6.84E+09	9.92E+09
60.0	36.62%	6.01E+09	8.72E+09
70.0	32.56%	5.34E+09	7.75E+09
80.0	29.26%	4.80E+09	6.96E+09
90.0	26.57%	4.36E+09	6.32E+09
100.0	24.38%	4.00E+09	5.80E+09
125.0	21.09%	3.46E+09	5.02E+09
150.0	17.80%	2.92E+09	4.24E+09
200.0	14.70%	2.41E+09	3.50E+09
250.0	12.91%	2.12E+09	3.07E+09
300.0	11.66%	1.91E+09	2.77E+09
400.0	9.87%	1.62E+09	2.35E+09
500.0	8.58%	1.41E+09	2.04E+09
600.0	7.57%	1.24E+09	1.80E+09
700.0	6.76%	1.11E+09	1.61E+09
800.0	6.08%	9.97E+08	1.45E+09
900.0	5.50%	9.03E+08	1.31E+09
1000.0	5.01%	8.23E+08	1.19E+09
1500.0	3.45%	5.67E+08	8.22E+08
2000.0	2.71%	4.45E+08	6.45E+08
3000.0	2.13%	3.49E+08	5.06E+08
4000.0	1.90%	3.12E+08	4.52E+08
5000.0	1.76%	2.88E+08	4.18E+08
6000.0	1.64%	2.69E+08	3.89E+08
7000.0	1.53%	2.51E+08	3.64E+08
8000.0	1.43%	2.35E+08	3.41E+08
9000.0	1.35%	2.21E+08	3.20E+08
10000.0	1.26%	2.07E+08	3.00E+08

Note: LL = Initial Linear Heat Load.

Table I-3. Volumetric Heat Generation Rates for Linear Heat Loads of 0.7 kW/m

Time (years)	Decay Percentage with respect to Initial Total Heat	LL=0.7 kW/m ($J/yr{\cdot}m^3$)
0.0	100.00%	1.15E+10
0.5	98.30%	1.13E+10
1.0	96.74%	1.11E+10
5.0	87.38%	1.00E+10
10.0	78.86%	9.06E+09
15.0	71.87%	8.26E+09
20.0	65.83%	7.56E+09
25.0	60.52%	6.95E+09
30.0	55.82%	6.41E+09
35.0	51.65%	5.94E+09
40.0	47.95%	5.51E+09
45.0	44.63%	5.13E+09
50.0	41.66%	4.79E+09
60.0	36.62%	4.21E+09
70.0	32.56%	3.74E+09
80.0	29.26%	3.36E+09
90.0	26.57%	3.05E+09
100.0	24.38%	2.80E+09
125.0	21.09%	2.42E+09
150.0	17.80%	2.05E+09
200.0	14.70%	1.69E+09
250.0	12.91%	1.48E+09
300.0	11.66%	1.34E+09
400.0	9.87%	1.13E+09
500.0	8.58%	9.86E+08
600.0	7.57%	8.70E+08
700.0	6.76%	7.76E+08
800.0	6.08%	6.98E+08
900.0	5.50%	6.32E+08
1000.0	5.01%	5.76E+08
1500.0	3.45%	3.97E+08
2000.0	2.71%	3.11E+08
3000.0	2.13%	2.44E+08
4000.0	1.90%	2.18E+08
5000.0	1.76%	2.02E+08
6000.0	1.64%	1.88E+08
7000.0	1.53%	1.76E+08
8000.0	1.43%	1.65E+08
9000.0	1.35%	1.55E+08
10000.0	1.26%	1.45E+08

Note: LL = Initial Linear Heat Load.

Table I-4. Volumetric Heat Generation Rates for Waste Packages with Additional 30 Years of Aging (Alternative Scenario Four)

Time (years)	Time Measured from Beginning of Emplacement (years)	Decay Percentage with respect to Initial Total Heat	LL=0.6 kW/m by 30-Yr Aging ($J/yr \cdot m^3$)
30.0	0	55.82%	9.16E+09
35.0	5.0	51.65%	8.48E+09
40.0	10.0	47.95%	7.87E+09
45.0	15.0	44.63%	7.33E+09
50.0	20.0	41.66%	6.84E+09
55.0	25.0	39.01%	6.40E+09
60.0	30.0	36.62%	6.01E+09
65.0	35.0	34.48%	5.66E+09
70.0	40.0	32.56%	5.34E+09
75.0	45.0	30.83%	5.06E+09
80.0	50.0	29.26%	4.8E+09
85.0	55.0	27.84%	4.57E+09
90.0	60.0	26.57%	4.36E+09
95.0	65.0	25.42%	4.17E+09
100.0	70.0	24.38%	4.00E+09
125.0	95.0	21.09%	3.46E+09
150.0	120.0	17.80%	2.92E+09
155.0	125.0	17.49%	2.87E+09
200.0	170.0	14.70%	2.41E+09
250.0	220.0	12.91%	2.12E+09
300.0	270.0	11.66%	1.91E+09
400.0	370.0	9.87%	1.62E+09
500.0	470.0	8.58%	1.41E+09
600.0	570.0	7.57%	1.24E+09
700.0	670.0	6.76%	1.11E+09
800.0	770.0	6.08%	9.97E+08
900.0	870.0	5.50%	9.03E+08
1000.0	970.0	5.01%	8.23E+08
1500.0	1470.0	3.45%	5.67E+08
2000.0	1970.0	2.71%	4.45E+08
3000.0	2970.0	2.13%	3.49E+08
4000.0	3970.0	1.90%	3.12E+08
5000.0	4970.0	1.76%	2.88E+08
6000.0	5970.0	1.64%	2.69E+08
7000.0	6970.0	1.53%	2.51E+08
8000.0	7970.0	1.43%	2.35E+08
9000.0	8970.0	1.35%	2.21E+08
10000.0	9970.0	1.26%	2.07E+08

Note: LL = Initial Linear Heat Load.

Table I-5. Volumetric Heat Generation Rates for 3D Model

Time (years)	21-PWR WP ($J/yr \cdot m^3$)		44-BWR WP ($J/yr \cdot m^3$)		DHLW Short WP ($J/yr \cdot m^3$)	
	Regular	Reduced	Regular	Reduced	Regular	Reduced
0.0	3.66E+10	9.53E+09	2.26E+10	5.87E+09	7.96E+09	2.07E+09
0.5	3.60E+10	9.36E+09	2.22E+10	5.77E+09	7.59E+09	1.97E+09
1.0	3.54E+10	9.21E+09	2.19E+10	5.68E+09	7.23E+09	1.88E+09
5.0[a]	3.20E+10	8.31E+09	1.98E+10	5.14E+09	6.09E+09	1.58E+09
10.0	2.88E+10	7.50E+09	1.79E+10	4.64E+09	5.39E+09	1.40E+09
15.0	2.63E+10	6.84E+09	1.63E+10	4.23E+09	4.80E+09	1.25E+09
20.0	2.41E+10	6.27E+09	1.49E+10	3.86E+09	4.29E+09	1.12E+09
25.0	2.22E+10	5.77E+09	1.36E+10	3.54E+09	3.83E+09	9.97E+08
30.0	2.05E+10	5.33E+09	1.25E+10	3.26E+09	3.57E+09	9.28E+08
35.0	1.90E+10	4.93E+09	1.16E+10	3.01E+09	3.21E+09	8.34E+08
40.0	1.76E+10	4.59E+09	1.07E+10	2.78E+09	2.88E+09	7.48E+08
45.0	1.64E+10	4.27E+09	9.92E+09	2.58E+09	2.59E+09	6.73E+08
50.0	1.54E+10	3.99E+09	9.23E+09	2.40E+09	2.32E+09	6.04E+08
60.0	1.35E+10	7.18E+09	8.06E+09	4.27E+09	1.89E+09	9.99E+08
70.0	1.21E+10	6.40E+09	7.12E+09	3.77E+09	1.54E+09	8.15E+08
80.0	1.09E+10	5.76E+09	6.36E+09	3.37E+09	1.26E+09	6.68E+08
90.0	9.89E+09	5.24E+09	5.74E+09	3.04E+09	1.04E+09	5.51E+08
100.0	9.10E+09	4.82E+09	5.24E+09	2.78E+09	8.62E+08	4.57E+08
125.0	7.89E+09	4.42E+09	4.50E+09	2.52E+09	5.60E+08	3.13E+08
150.0	6.69E+09	3.74E+09	3.76E+09	2.10E+09	3.77E+08	2.11E+08
200.0	5.53E+09	3.10E+09	3.08E+09	1.73E+09	1.98E+08	1.11E+08
250.0	4.86E+09	2.72E+09	2.71E+09	1.52E+09	1.23E+08	6.87E+07
300.0	4.38E+09	2.46E+09	2.45E+09	1.37E+09	8.50E+07	4.76E+07

[a] Sample calculation for the 21-PWR waste package at year 5:
(applicable for the 44-BWR and the DHLW waste packages as well)

Given:	1 watt = 1 joule/sec	p. I-2	
	3.1536E+07 sec/yr	p. I-2	
	10.0546 kW/pk	(Table I-1)	
	5.165 m	21-PWR length	p. I-2
	1.564 m	21-PWR diameter	p. I-2

10.0546 kW = 10054.6 j/sec

10054.6 j/sec (3.1536E+07 sec/yr) = 3.1708E+11 j/yr

$5.165\ [\pi\ (1.564\ /2)^2] = 9.923\ \mathrm{m}^3$

$$\frac{3.1708\mathrm{E}{+}11\ \mathrm{j/yr}}{9.923\ \mathrm{m}^3} = 3.20\ \mathrm{E}{+}10\ \frac{\mathrm{j/yr}}{\mathrm{m}^3}$$

ATTACHMENT II

TEMPERATURES AND VENTILATION EFFICIENCY FOR BASE CASE

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 1.45 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 300 years. This represents the SR base case. Ventilation efficiency is calculated for up to 300 years. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table II-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m and 15 m^3/s (0-300 Years) (Base Case)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.91	25.91	25.91	25.91	25.91
1.0	37.41	43.76	48.28	51.56	53.93	55.65
5.0	36.38	44.37	51.69	58.11	63.56	68.11
10.0	35.32	42.70	50.02	57.12	63.83	70.05
15.0	34.37	41.12	47.85	54.56	61.17	67.63
20.0	33.60	39.79	45.98	52.15	58.31	64.42
25.0	32.88	38.58	44.28	49.98	55.66	61.34
30.0	32.27	37.53	42.80	48.07	53.34	58.60
40.0	31.22	35.93	40.69	45.48	50.30	55.13
50.0	30.41	34.49	38.66	42.91	47.22	51.58
60.0	29.75	33.34	37.00	40.73	44.53	48.40
70.0	29.22	32.40	35.64	38.95	42.31	45.74
80.0	28.79	31.64	34.54	37.50	40.50	43.57
90.0	28.44	31.03	33.64	36.31	39.03	41.79
100.0	28.16	30.53	32.92	35.35	37.82	40.33
125.0	27.74	29.84	32.00	34.20	36.44	38.71
150.0	27.32	29.13	31.00	32.94	34.93	36.95
200.0	26.91	28.44	30.03	31.67	33.38	35.15
250.0	26.68	27.98	29.33	30.74	32.19	33.70
300.0	26.52	27.68	28.87	30.09	31.36	32.67

Source: DTN: MO0107MWDTEM05.011

Table II-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m and 15 m^3/s (0-300 Years) (Base Case)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.01	30.03	30.03	30.03	30.03	30.03
1.0	31.83	36.84	40.46	43.09	44.99	46.37
5.0	33.31	40.97	47.71	53.46	58.26	62.21
10.0	32.59	40.14	47.50	54.49	60.98	66.87
15.0	31.91	38.82	45.72	52.55	59.24	65.70
20.0	31.33	37.66	43.99	50.32	56.62	62.86
25.0	30.82	36.64	42.47	48.30	54.13	59.95
30.0	30.36	35.74	41.12	46.51	51.90	57.29
40.0	29.79	34.64	39.53	44.45	49.40	54.36
50.0	29.14	33.38	37.70	42.09	46.54	51.04
60.0	28.63	32.34	36.13	39.99	43.93	47.93
70.0	28.21	31.49	34.84	38.25	41.73	45.28
80.0	27.87	30.80	33.79	36.83	39.93	43.09
90.0	27.60	30.24	32.93	35.67	38.46	41.29
100.0	27.38	29.79	32.24	34.73	37.26	39.83
125.0	27.12	29.29	31.51	33.77	36.06	38.40
150.0	26.82	28.70	30.65	32.65	34.69	36.79
200.0	26.53	28.12	29.77	31.49	33.27	35.10
250.0	26.30	27.65	29.06	30.52	32.03	33.61
300.0	26.16	27.35	28.57	29.84	31.15	32.51

Source: DTN: MO0107MWDTEM05.011

Table II-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m and 15 m^3/s (0-300 Years) (Base Case)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.96	67.03	67.03	67.03	67.03	67.03
1.0	60.04	65.75	69.82	72.79	74.94	76.50
5.0	57.23	64.39	71.00	76.81	81.77	85.92
10.0	54.36	61.02	67.65	74.12	80.27	85.99
15.0	51.88	58.01	64.15	70.30	76.38	82.35
20.0	49.81	55.48	61.15	66.84	72.53	78.20
25.0	47.87	53.12	58.38	63.66	68.94	74.23
30.0	46.21	51.08	55.98	60.88	65.80	70.72
40.0	43.31	47.72	52.19	56.69	61.22	65.79
50.0	41.03	44.88	48.82	52.84	56.93	61.07
60.0	39.16	42.56	46.04	49.60	53.22	56.92
70.0	37.63	40.67	43.77	46.93	50.15	53.44
80.0	36.38	39.11	41.90	44.74	47.63	50.57
90.0	35.37	37.85	40.37	42.94	45.55	48.22
100.0	34.53	36.82	39.13	41.48	43.86	46.29
125.0	33.28	35.32	37.41	39.55	41.73	43.93
150.0	32.02	33.79	35.61	37.50	39.44	41.41
200.0	30.82	32.31	33.86	35.47	37.14	38.87
250.0	30.11	31.39	32.71	34.09	35.52	36.99
300.0	29.62	30.76	31.93	33.13	34.37	35.66

Source: DTN: MO0107MWDTEM05.011

Table II-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 1.45 kW/m and 15 m^3/s (0-300 Years) (Base Case)

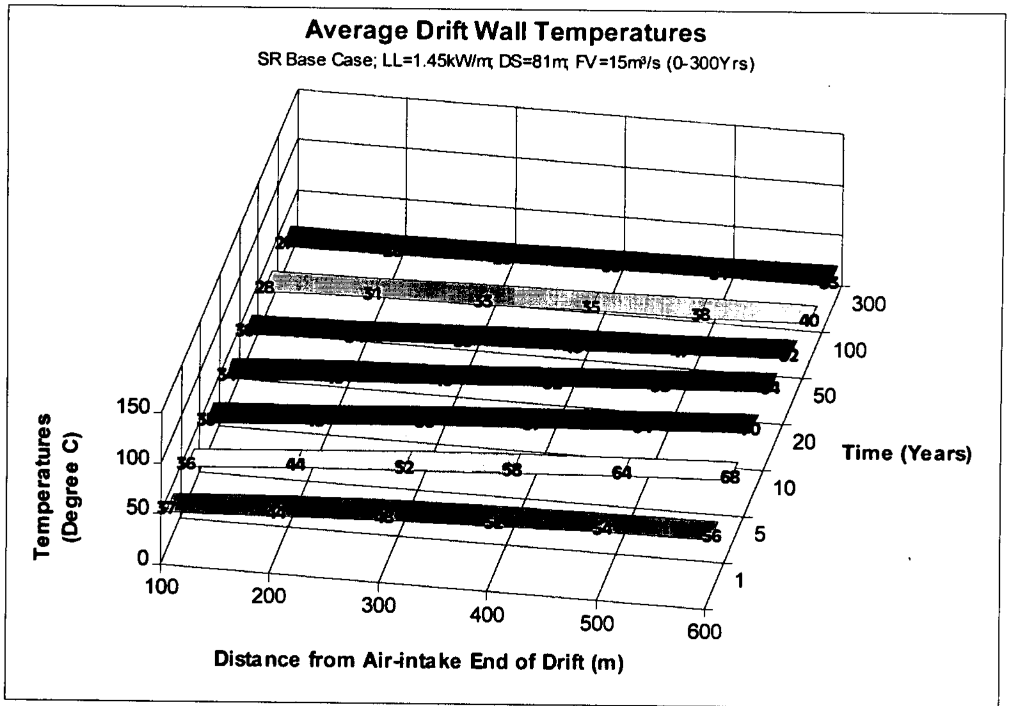
Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.67	66.95	66.95	66.95	66.95	66.95
1.0	90.87	84.57	79.31	75.53	72.81	70.82
5.0	110.56	105.86	100.50	95.55	91.17	87.37
10.0	101.01	98.60	95.72	92.49	89.01	85.49
15.0	91.92	90.17	88.28	86.22	83.90	81.39
20.0	84.17	82.75	81.23	79.66	77.99	76.19
25.0	77.39	76.20	74.91	73.59	72.25	70.84
30.0	71.33	70.31	69.25	68.13	67.00	65.83
40.0	63.73	63.00	62.22	61.35	60.43	59.49
50.0	55.14	54.70	54.20	53.62	52.97	52.29
60.0	48.31	47.99	47.66	47.29	46.85	46.41
70.0	42.76	42.53	42.30	42.05	41.73	41.42
80.0	38.25	38.06	37.90	37.74	37.50	37.28
90.0	34.58	34.45	34.32	34.19	34.03	33.88
100.0	31.60	31.53	31.40	31.30	31.19	31.07
125.0	28.25	28.22	28.16	28.11	28.04	27.93
150.0	24.23	24.27	24.29	24.34	24.33	24.24
200.0	20.31	20.42	20.48	20.56	20.62	20.63
250.0	17.28	17.39	17.47	17.55	17.64	17.69
300.0	15.38	15.46	15.53	15.59	15.68	15.72

Source: DTN: MO0107MWDTEM05.011

Table II-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 1.45 kW/m and 15 m^3/s (0-300 Years) (Base Case)

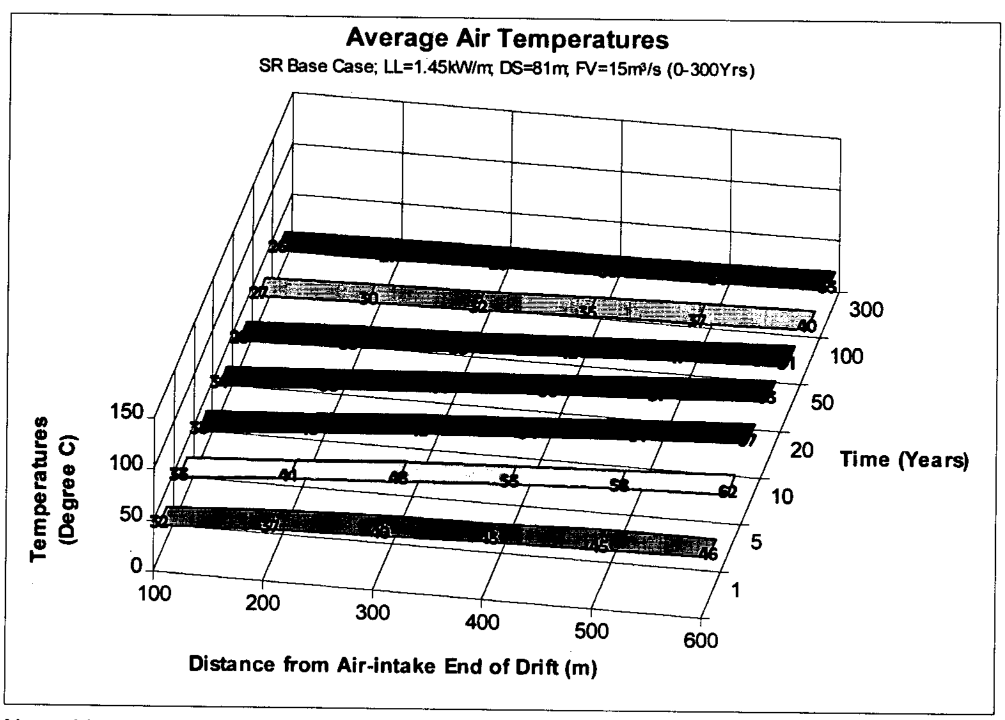
Time (years)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (years)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	870.00	870.00	2.74	1.00E-04	401.40	200.70	0.63
1.0	96.74%	841.63	855.82	26986.34	1.0	473.91	437.66	13800.56
5.0	87.38%	760.22	800.93	101031.99	5.0	591.00	532.45	67165.99
10.0	78.86%	686.11	723.17	114028.75	10.0	562.33	576.67	90928.55
15.0	71.87%	625.27	655.69	103389.54	15.0	521.88	542.11	85479.18
20.0	65.83%	572.71	598.99	94448.98	20.0	481.99	501.93	79144.98
25.0	60.52%	526.49	549.60	86660.82	25.0	445.18	463.58	73098.01
30.0	55.82%	485.65	506.07	79796.67	30.0	411.85	428.51	67567.93
40.0	47.95%	417.15	451.40	142352.80	40.0	370.22	391.03	123315.80
50.0	41.66%	362.42	389.78	122922.17	50.0	322.92	346.57	109294.54
60.0	36.62%	318.62	340.52	107386.87	60.0	284.50	303.71	95778.01
70.0	32.56%	283.25	300.94	94903.41	70.0	252.79	268.64	84718.93
80.0	29.26%	254.56	268.90	84801.55	80.0	226.74	239.76	75611.37
90.0	26.57%	231.14	242.85	76584.99	90.0	205.45	216.09	68146.85
100.0	24.38%	212.12	221.63	69893.78	100.0	188.09	196.77	62052.32
125.0	21.09%	183.51	197.82	155957.83	125.0	168.72	178.40	140650.95
150.0	17.80%	154.89	169.20	133398.33	150.0	145.69	157.20	123937.23
200.0	14.70%	127.92	141.41	222968.18	200.0	123.03	134.36	211854.27
250.0	12.91%	112.36	120.14	189434.61	250.0	105.01	114.02	179787.67
300.0	11.66%	101.42	106.89	168548.44	300.0	93.37	99.19	156404.76
Total heat generated in 25 years (GJ)				526549.17	Total heat removed in 25 years (GJ)			409617.90
Total heat generated in 50 years (GJ)				871620.81	Total heat removed in 50 years (GJ)			709796.17
Total heat generated in 100 years (GJ)				1305191.42	Total heat removed in 100 years (GJ)			1096103.65
Total heat generated in 300 years (GJ)				2175498.80	Total heat removed in 300 years (GJ)			1908738.53
Percentage of total heat removal in 25 years = 78%								
Percentage of total heat removal in 50 years = 81%								
Percentage of total heat removal in 100 years = 84%								
Percentage of total heat removal in 300 years = 88%								

Source: DTN: MO0107MWDTEM05.011



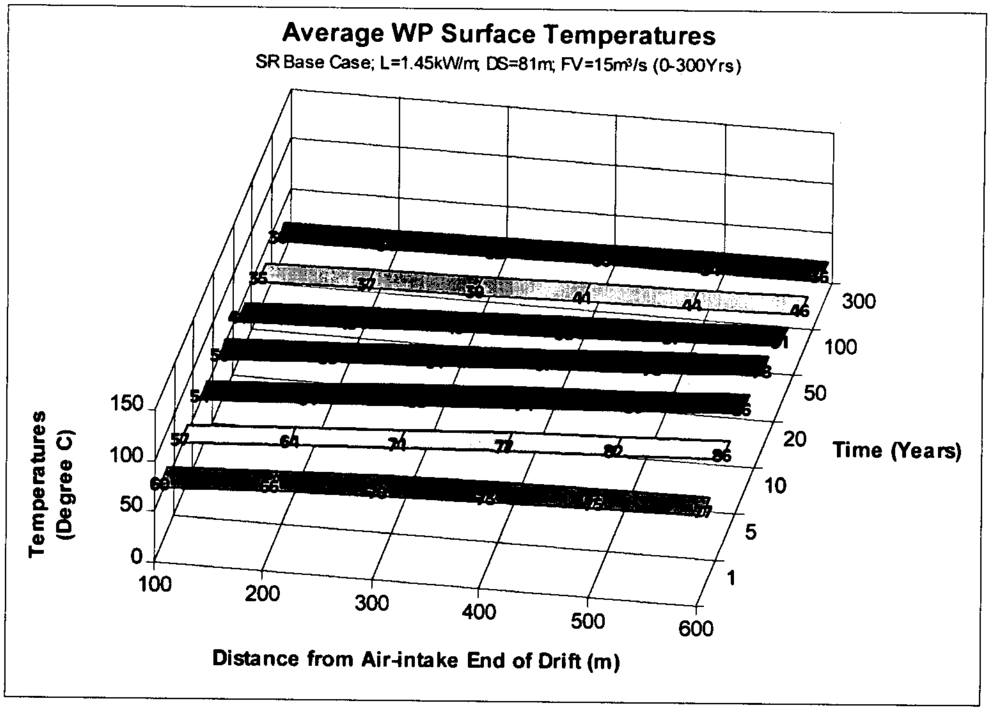
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure II-1. Average Drift Wall Temperatures for Base Case



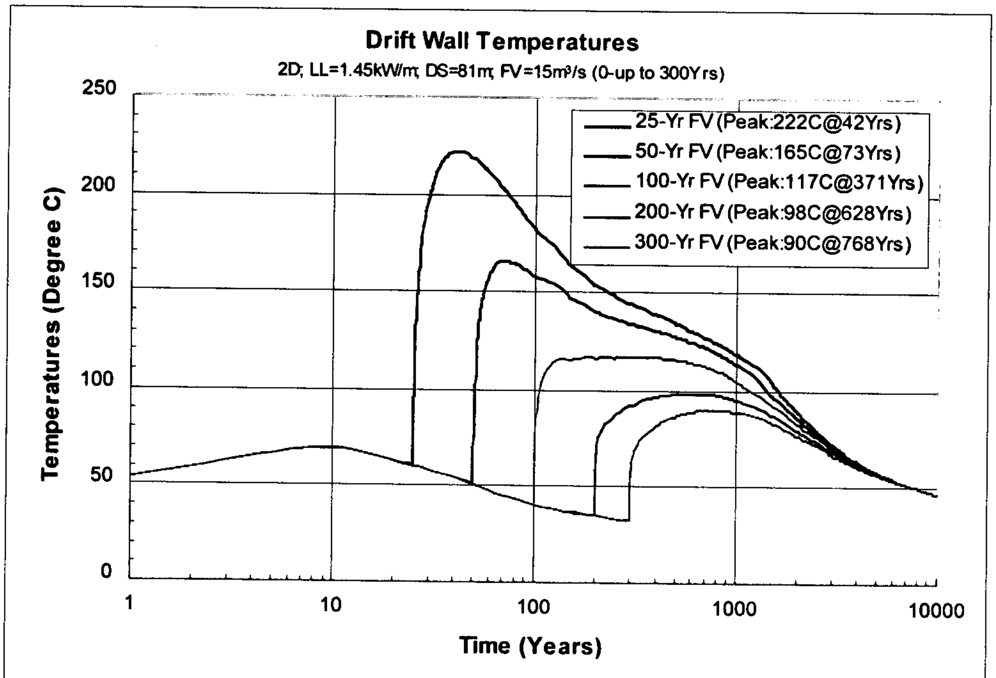
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure II-2. Average Air Temperatures for Base Case



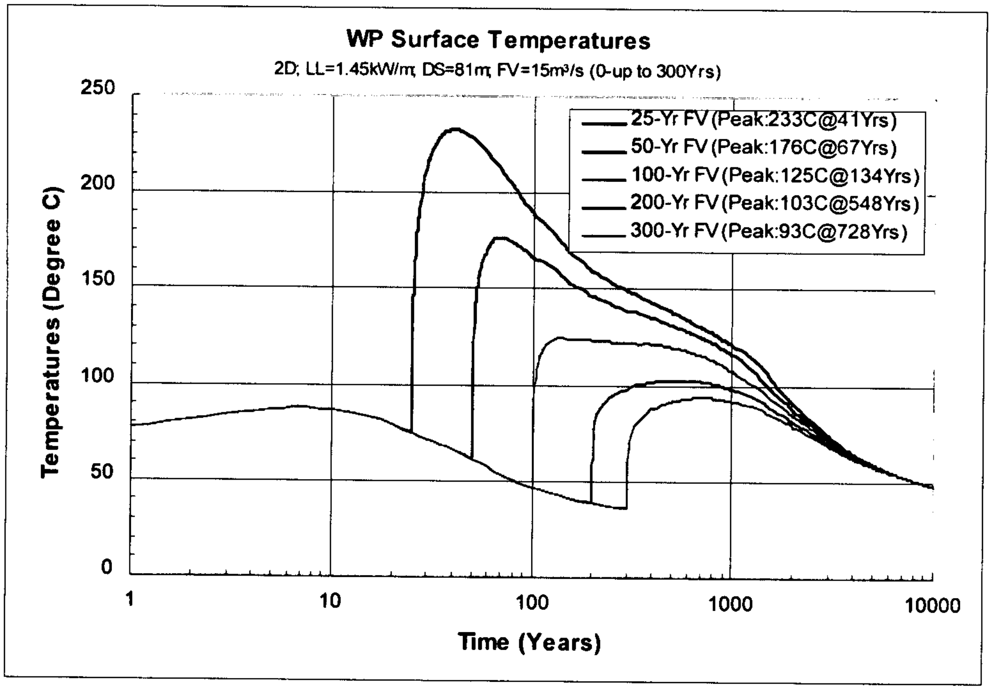
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure II-3. Average Waste Package Surface Temperatures for Base Case



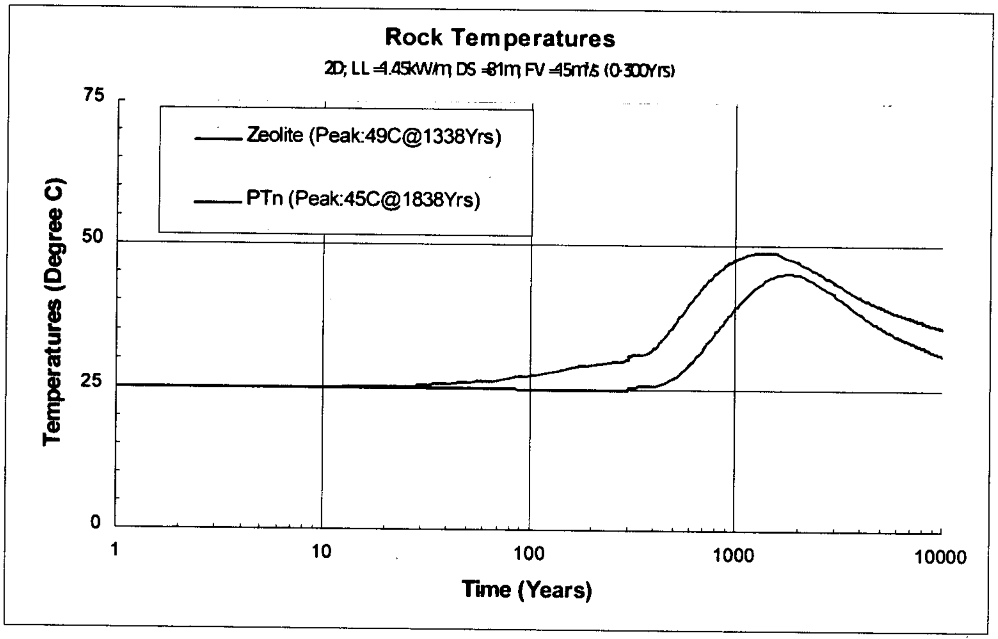
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-4. Drift Wall Temperatures with Different Ventilation Durations for Base Case



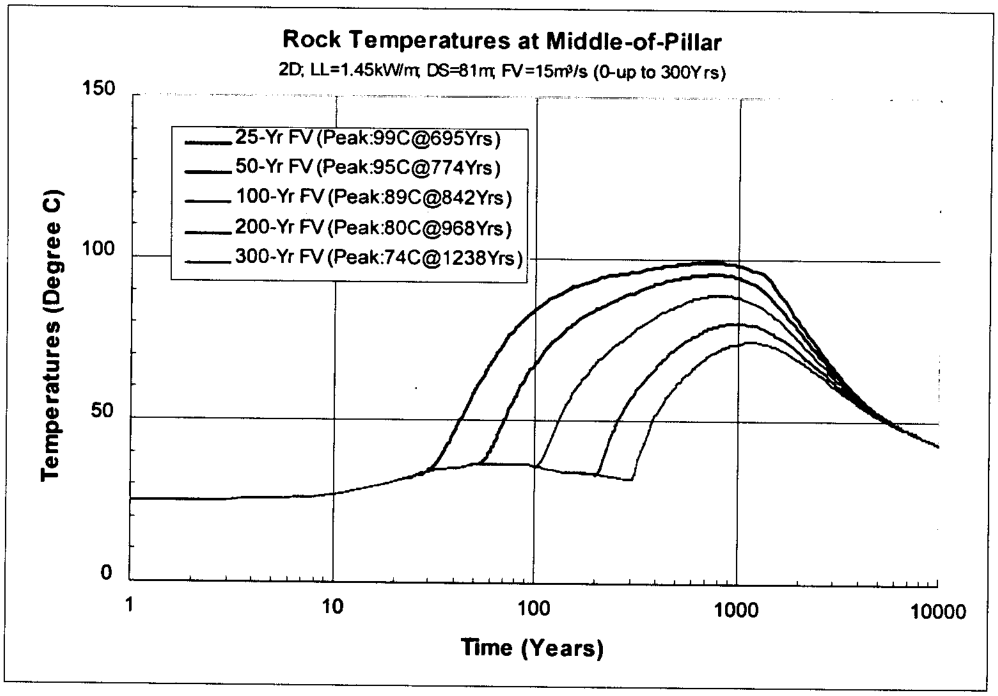
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-5. WP Surface Temperatures with Different Ventilation Durations for Base Case



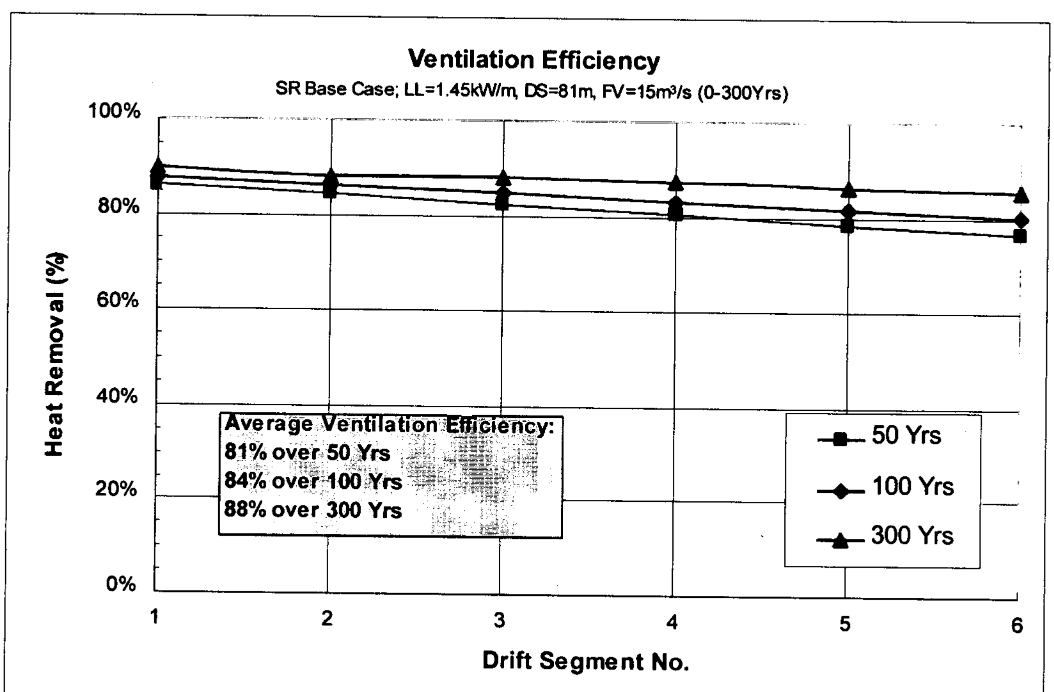
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-6. Rock Temperatures at Zeolite and PTn Unit with Different Ventilation Durations for Base Case



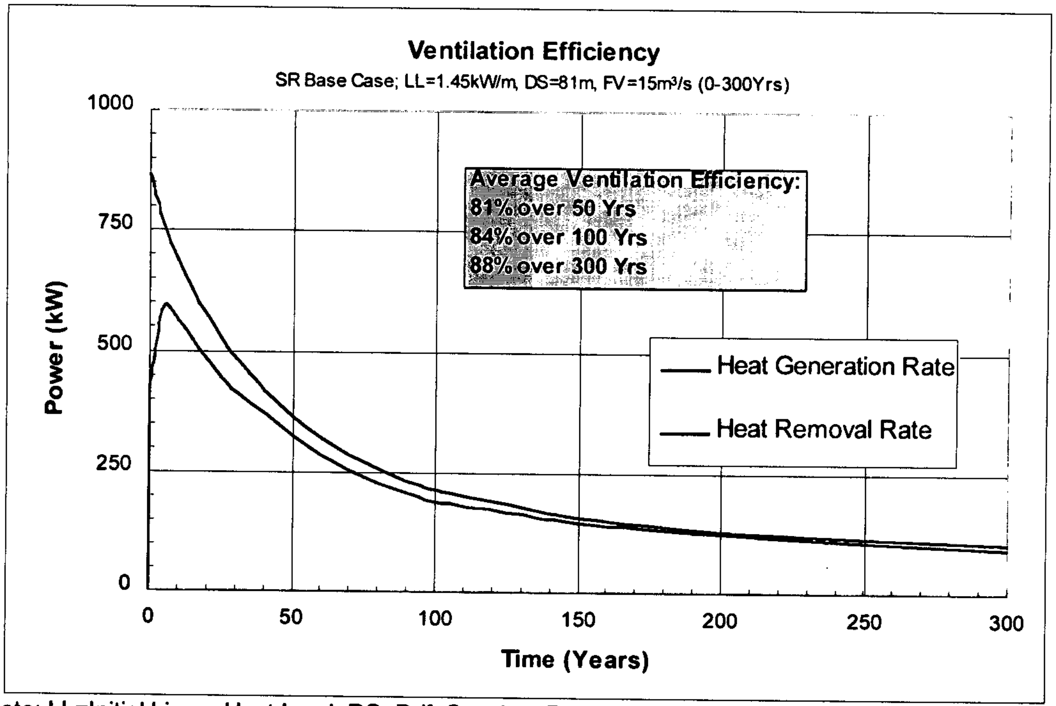
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-7. Rock Temperatures at Middle-of-Pillar with Different Ventilation Durations for Base Case



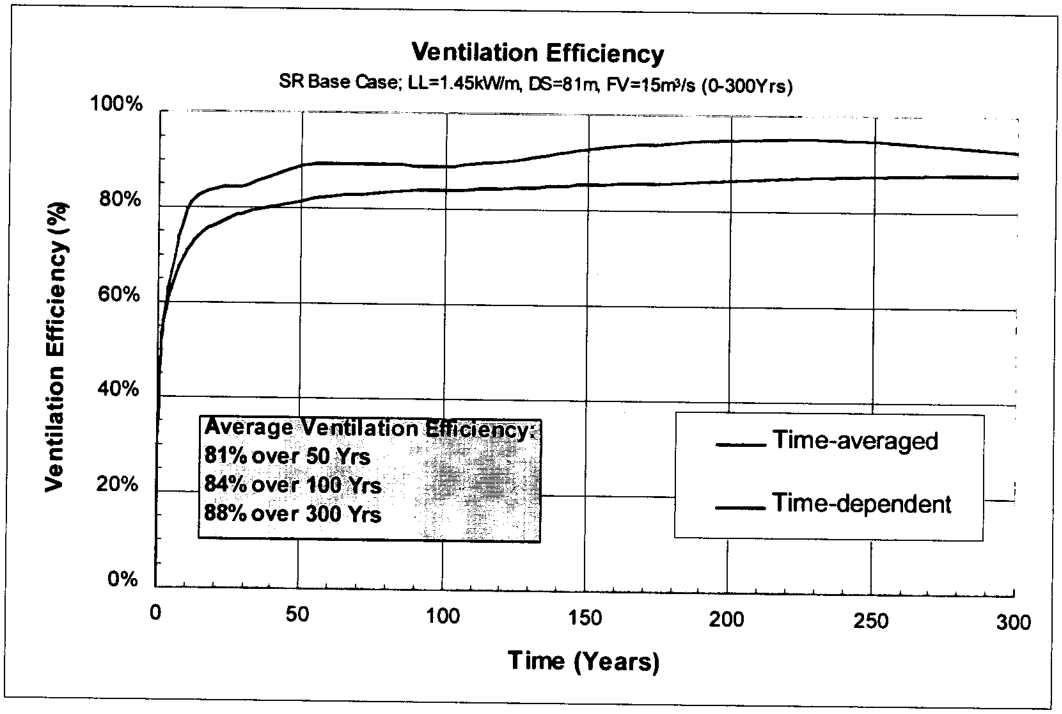
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure II-8. Average Heat Removal Rates at Different Drift Segments for Base Case



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-9. Overall Heat Generation and Removal Rates at Different Time for Base Case



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure II-10. Time-averaged and Time-dependent Ventilation Efficiencies for Base Case

ATTACHMENT III

TEMPERATURES AND VENTILATION EFFICIENCY FOR THE REPRESENTATIVE SCENARIO

Note: The *Representative Scenario* and *Alternative Scenario One* are considered the same in the 2D ANSYS since they both have the same thermal load of 1.0 kW/m and waste package spacing is not a factor for two-dimensional analysis.

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 1.0 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 50 years and natural ventilation air flow rates of 3 m^3/s from 50 to 100 years and 1.5 m^3/s from 100 to 300 years. This case represents *Representative Scenario* of the low temperature repository design. Ventilation efficiency is calculated for up to 300 years. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table III-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

Time (Years)	**Location Measured from Air-intake End (m)**							
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800
0.0	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.90	25.90	25.90	25.90	25.90	25.90	25.90
1.0	33.47	38.57	42.20	44.83	46.74	48.12	49.13	49.86
5.0	32.69	38.19	43.41	48.08	52.11	55.52	58.33	60.64
10.0	31.96	37.02	42.03	46.96	51.69	56.10	60.15	63.79
15.0	31.37	35.99	40.60	45.21	49.76	54.25	58.60	62.76
20.0	30.83	35.08	39.32	43.56	47.80	52.01	56.19	60.30
25.0	30.36	34.27	38.18	42.09	46.01	49.91	53.81	57.69
30.0	29.95	33.55	37.17	40.79	44.41	48.03	51.65	55.26
40.0	29.25	32.48	35.74	39.04	42.36	45.68	49.02	52.37
50.0	28.69	31.50	34.37	37.28	40.25	43.26	46.28	49.34
60.0	37.99	44.01	48.56	52.25	55.42	58.30	61.01	63.62
70.0	36.79	45.08	51.84	57.29	61.71	65.38	68.52	71.30
80.0	35.73	43.48	50.65	57.00	62.48	67.14	71.10	74.48
90.0	34.84	42.01	48.76	55.04	60.79	65.94	70.50	74.47
100.0	34.10	40.76	47.08	53.02	58.60	63.76	68.49	72.77
125.0	38.01	45.93	52.40	57.98	62.95	67.47	71.61	75.40
150.0	36.41	45.01	52.23	58.27	63.43	67.90	71.87	75.44
200.0	34.73	42.49	49.62	55.94	61.43	66.18	70.31	73.95
250.0	33.74	40.68	47.22	53.29	58.80	63.72	68.06	71.87
300.0	33.00	39.38	45.41	51.09	56.38	61.23	65.62	69.56

Source: DTN: MO0107MWDTEM05.011

Table III-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

Time (Years)	Location Measured from Air-intake End (m)							
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800
0.0	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.01	30.03	30.03	30.03	30.03	30.03	30.03	30.03
1.0	30.49	34.53	37.46	39.58	41.12	42.24	43.05	43.63
5.0	30.74	36.22	41.14	45.41	49.02	52.01	54.46	56.43
10.0	30.22	35.42	40.55	45.48	50.10	54.35	58.17	61.56
15.0	29.75	34.51	39.27	43.99	48.65	53.18	57.52	61.61
20.0	29.36	33.72	38.09	42.46	46.81	51.14	55.41	59.59
25.0	29.01	33.02	37.04	41.07	45.09	49.11	53.12	57.10
30.0	28.69	32.40	36.11	39.83	43.55	47.27	50.99	54.71
40.0	28.30	31.64	35.02	38.42	41.83	45.26	48.70	52.14
50.0	27.86	30.78	33.76	36.79	39.87	42.97	46.10	49.25
60.0	31.91	37.08	41.23	44.78	47.98	50.99	53.88	56.72
70.0	34.66	42.56	48.89	53.99	58.18	61.72	64.83	67.64
80.0	33.77	41.98	49.30	55.62	60.98	65.51	69.35	72.66
90.0	33.01	40.60	47.72	54.27	60.15	65.35	69.88	73.82
100.0	32.37	39.40	46.05	52.31	58.14	63.49	68.34	72.68
125.0	34.55	42.30	48.96	54.89	60.29	65.23	69.76	73.89
150.0	35.33	44.01	51.23	57.34	62.61	67.26	71.43	75.21
200.0	33.93	42.24	49.64	56.07	61.62	66.43	70.64	74.36
250.0	32.79	40.21	47.15	53.49	59.17	64.18	68.57	72.44
300.0	32.05	38.77	45.14	51.11	56.62	61.63	66.13	70.14

Source: DTN: MO0107MWDTEM05.011

Table III-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

Time (Years)	Location Measured from Air-intake End (m)							
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800
0.0	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.86	66.93	66.93	66.93	66.93	66.93	66.93	66.93
1.0	49.73	54.49	57.89	60.36	62.16	63.46	64.41	65.09
5.0	47.65	52.76	57.62	61.99	65.77	68.97	71.62	73.78
10.0	45.55	50.26	54.96	59.58	64.02	68.19	72.01	75.45
15.0	43.89	48.21	52.55	56.88	61.18	65.42	69.54	73.49
20.0	42.36	46.36	50.36	54.37	58.38	62.37	66.34	70.26
25.0	41.01	44.72	48.42	52.13	55.86	59.57	63.28	66.99
30.0	39.82	43.25	46.69	50.14	53.59	57.05	60.50	63.96
40.0	37.80	40.89	44.02	47.19	50.37	53.57	56.78	60.00
50.0	36.17	38.88	41.64	44.45	47.31	50.22	53.14	56.09
60.0	46.18	51.91	56.25	59.76	62.79	65.54	68.13	70.63
70.0	44.13	52.10	58.62	63.87	68.14	71.68	74.71	77.39
80.0	42.39	49.85	56.77	62.93	68.24	72.77	76.61	79.89
90.0	40.93	47.85	54.38	60.48	66.07	71.09	75.52	79.40
100.0	39.73	46.17	52.30	58.08	63.50	68.54	73.15	77.33
125.0	43.07	50.77	57.06	62.49	67.34	71.75	75.80	79.50
150.0	40.72	49.12	56.20	62.12	67.16	71.55	75.44	78.94
200.0	38.33	45.93	52.93	59.15	64.55	69.23	73.30	76.88
250.0	36.92	43.74	50.17	56.14	61.58	66.43	70.71	74.48
300.0	35.88	42.15	48.09	53.69	58.91	63.70	68.04	71.93

Source: DTN: MO0107MWDTEM05.011

Table III-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Spatial Correction for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

Time (Years)	Location Measured from Air-intake End (m)							
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	60.02	60.27	60.27	60.27	60.27	60.27	60.27	60.27
1.0	65.89	48.46	35.10	25.45	18.44	13.37	9.70	7.04
5.0	68.82	65.74	59.06	51.20	43.26	35.88	29.32	23.69
10.0	62.57	62.43	61.45	59.11	55.50	50.93	45.84	40.56
15.0	57.02	57.06	57.00	56.71	55.83	54.28	52.05	49.14
20.0	52.28	52.34	52.36	52.37	52.22	51.88	51.23	50.16
25.0	48.04	48.16	48.20	48.26	48.29	48.19	48.05	47.75
30.0	44.31	44.43	44.52	44.58	44.65	44.64	44.61	44.54
40.0	39.60	40.07	40.46	40.76	40.98	41.10	41.21	41.27
50.0	34.29	35.07	35.74	36.34	36.84	37.24	37.55	37.80
60.0	14.49	10.86	8.70	7.45	6.72	6.31	6.07	5.95
70.0	20.27	16.58	13.29	10.70	8.79	7.44	6.51	5.89
80.0	18.40	17.22	15.36	13.26	11.25	9.49	8.06	6.94
90.0	16.81	15.92	14.94	13.73	12.35	10.90	9.51	8.25
100.0	15.47	14.73	13.96	13.14	12.23	11.23	10.17	9.10
125.0	9.29	7.54	6.48	5.77	5.25	4.81	4.41	4.02
150.0	10.05	8.45	7.03	5.94	5.13	4.53	4.06	3.67
200.0	8.68	8.09	7.20	6.26	5.40	4.68	4.09	3.62
250.0	7.58	7.22	6.76	6.17	5.52	4.87	4.28	3.76
300.0	6.86	6.54	6.20	5.81	5.36	4.88	4.38	3.90

Source: DTN: MO0107MWDTEM05.011

Table III-5. Calculation of Overall Ventilation Efficiency Based on Spatial Correction for 600m-long Drift for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

Time (year)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (year)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	600.00	600.00	1.89	1.00E-04	361.39	180.70	0.57
1.0	96.74%	580.44	590.22	18611.27	1.0	206.71	284.05	8956.96
5.0	87.38%	524.29	552.36	69677.23	5.0	323.94	265.33	33469.53
10.0	78.86%	473.18	498.73	78640.52	10.0	352.00	337.97	53291.42
15.0	71.87%	431.22	452.20	71303.13	15.0	337.90	344.95	54391.64
20.0	65.83%	394.97	413.10	65137.23	20.0	313.46	325.68	51353.37
25.0	60.52%	363.09	379.03	59766.08	25.0	289.15	301.31	47510.11
30.0	55.82%	334.93	349.01	55032.19	30.0	267.13	278.14	43857.11
40.0	47.95%	287.69	311.31	98174.34	40.0	242.98	255.05	80433.87
50.0	41.66%	249.94	268.82	84773.91	50.0	215.52	229.25	72296.51
60.0	36.62%	219.74	234.84	74059.91	60.0	54.52	135.02	42580.61
70.0	32.56%	195.34	207.54	65450.63	70.0	77.05	65.79	20747.30
80.0	29.26%	175.56	185.45	58483.83	80.0	84.99	81.02	25551.75
90.0	26.57%	159.41	167.48	52817.23	90.0	84.66	84.83	26750.59
100.0	24.38%	146.29	152.85	48202.61	100.0	80.76	82.71	26083.11
125.0	21.09%	126.56	136.42	107557.12	125.0	39.14	59.95	47266.50
150.0	17.80%	106.82	116.69	91998.85	150.0	41.11	40.13	31638.23
200.0	14.70%	88.22	97.52	153771.16	200.0	40.31	40.71	64193.51
250.0	12.91%	77.49	82.85	130644.56	250.0	38.11	39.21	61828.27
300.0	11.66%	69.95	73.72	116240.31	300.0	35.64	36.88	58149.73
Total heat generated in 25 years (GJ)				363137.36	Total heat removed in 25 years (GJ)			248973.61
Total heat generated in 50 years (GJ)				601117.80	Total heat removed in 50 years (GJ)			445561.10
Total heat generated from 50 to 100 years (GJ)				299014.21	Total heat removed from 50 to 100 years (GJ)			141713.35
Total heat generated from 100 to 300 years (GJ)				600211.99	Total heat removed from 100 to 300 years (GJ)			263076.24
Percentage of total heat removal in 25 years = 69%								
Percentage of total heat removal in 50 years = 74%								
Percentage of total heat removal from 50 to 100 years = 47%								
Percentage of total heat removal from 100 to 300 years = 44%								

Source: DTN: MO0107MWDTEM05.011

Table III-6. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

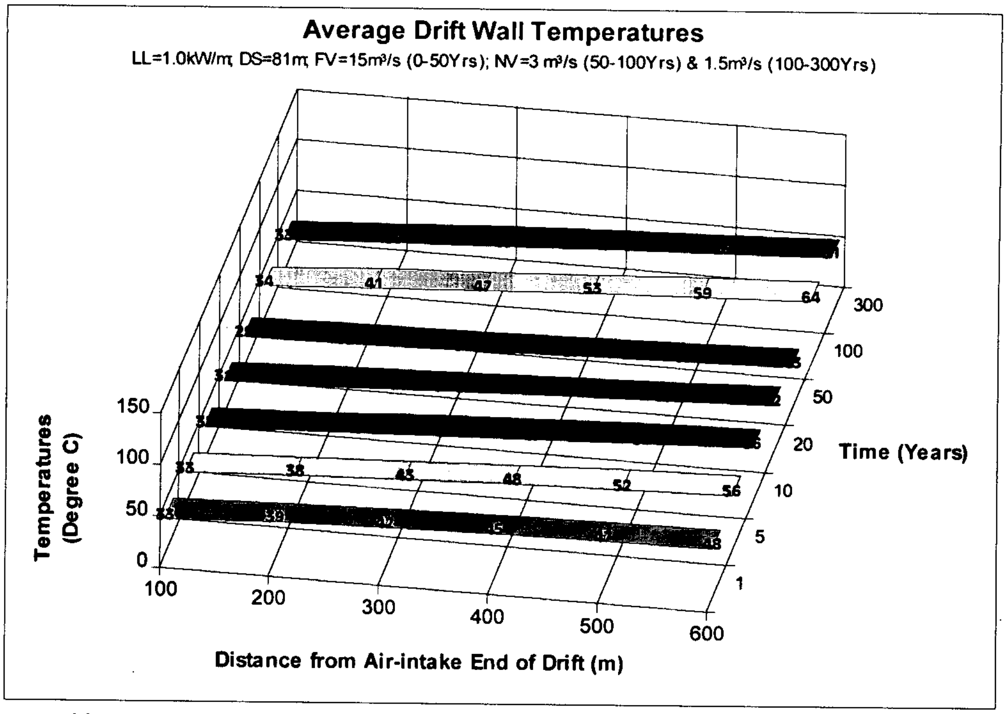
Time (Years)	Location Measured from Air-intake End (m)							
	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.60	66.87	66.87	66.87	66.87	66.87	60.27	60.27
1.0	73.11	68.19	63.98	60.96	58.76	57.17	9.70	7.04
5.0	76.35	73.57	69.95	66.47	63.30	60.55	29.32	23.69
10.0	69.42	67.90	66.09	64.02	61.74	59.36	45.84	40.56
15.0	63.26	62.10	60.85	59.55	58.05	56.40	52.05	49.14
20.0	58.01	57.03	56.03	55.02	53.91	52.73	51.23	50.16
25.0	53.30	52.51	51.64	50.79	49.92	48.95	48.05	47.75
30.0	49.16	48.47	47.76	47.02	46.29	45.48	44.61	44.54
40.0	43.94	43.43	42.91	42.35	41.76	41.09	41.21	41.27
50.0	38.04	37.75	37.39	37.03	36.61	36.15	37.55	37.80
60.0	17.00	15.67	14.77	14.15	13.67	13.29	6.07	5.95
70.0	23.78	21.44	19.56	18.11	16.99	16.12	6.51	5.89
80.0	21.59	19.55	17.60	15.85	14.38	13.17	8.06	6.94
90.0	19.71	18.12	16.53	14.96	13.50	12.18	9.51	8.25
100.0	18.15	16.82	15.51	14.19	12.92	11.71	10.17	9.10
125.0	11.26	10.04	9.06	8.20	7.43	6.72	4.41	4.02
150.0	12.18	10.56	9.23	8.14	7.23	6.45	4.06	3.67
200.0	10.53	9.22	8.00	6.93	6.03	5.26	4.09	3.62
250.0	9.19	8.28	7.35	6.45	5.62	4.89	4.28	3.76
300.0	8.32	7.63	6.92	6.21	5.51	4.86	4.38	3.90

Source: DTN: MO0107MWDTEM05.011

Table III-7. Calculation of Overall Ventilation Efficiency Based on Combined Spatial Temporal Correction for 600m-long Drift for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario)

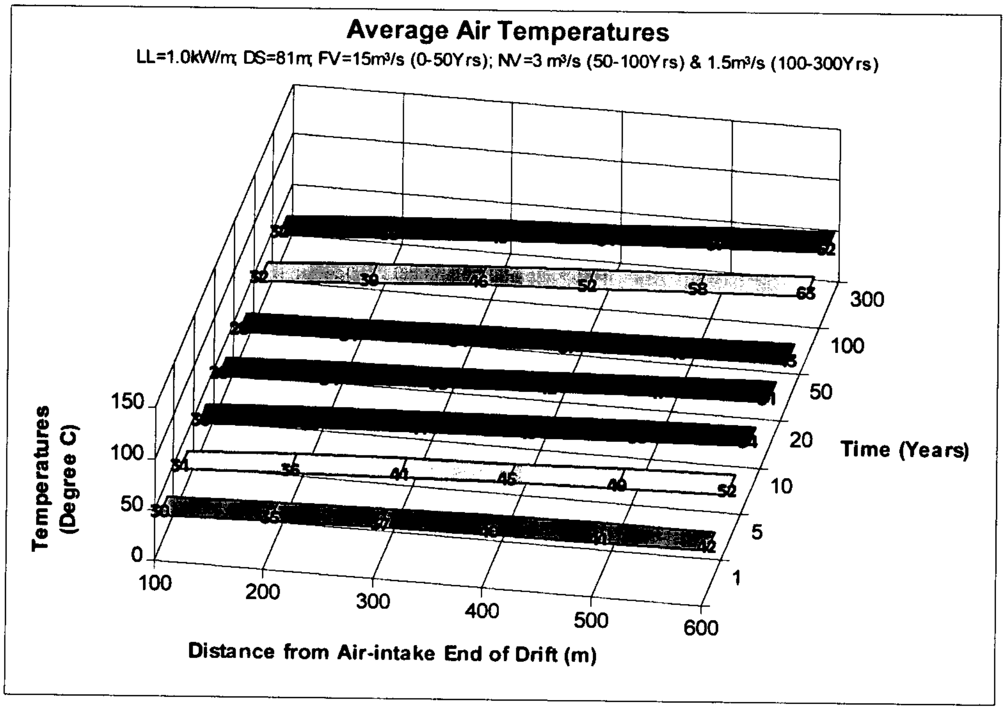
Time (year)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (year)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	600.00	600.00	1.89	1.00E-04	400.96	200.48	0.63
1.0	96.74%	580.44	590.22	18611.27	1.0	382.17	391.57	12347.24
5.0	87.38%	524.29	552.36	69677.23	5.0	410.20	396.19	49976.77
10.0	78.86%	473.18	498.73	78640.52	10.0	388.52	399.36	62971.40
15.0	71.87%	431.22	452.20	71303.13	15.0	360.21	374.37	59030.30
20.0	65.83%	394.97	413.10	65137.23	20.0	332.72	346.47	54631.28
25.0	60.52%	363.09	379.03	59766.08	25.0	307.12	319.92	50445.09
30.0	55.82%	334.93	349.01	55032.19	30.0	284.19	295.65	46618.27
40.0	47.95%	287.69	311.31	98174.34	40.0	255.48	269.83	85093.70
50.0	41.66%	249.94	268.82	84773.91	50.0	222.97	239.22	75441.90
60.0	36.62%	219.74	234.84	74059.91	60.0	88.54	155.76	49119.95
70.0	32.56%	195.34	207.54	65450.63	70.0	116.00	102.27	32252.24
80.0	29.26%	175.56	185.45	58483.83	80.0	102.13	109.07	34394.87
90.0	26.57%	159.41	167.48	52817.23	90.0	95.01	98.57	31084.86
100.0	24.38%	146.29	152.85	48202.61	100.0	89.30	92.15	29061.28
125.0	21.09%	126.56	136.42	107557.12	125.0	52.72	71.01	55983.49
150.0	17.80%	106.82	116.69	91998.85	150.0	53.79	53.26	41986.90
200.0	14.70%	88.22	97.52	153771.16	200.0	45.97	49.88	78654.18
250.0	12.91%	77.49	82.85	130644.56	250.0	41.79	43.88	69194.65
300.0	11.66%	69.95	73.72	116240.31	300.0	39.45	40.62	64050.77
Total heat generated in 25 years (GJ)				363137.36	Total heat removed in 25 years (GJ)			289402.71
Total heat generated in 50 years (GJ)				601117.80	Total heat removed in 50 years (GJ)			496556.58
Total heat generated from 50 to 100 years (GJ)				299014.21	Total heat removed from 50 to 100 years (GJ)			175913.21
Total heat generated from 100 to 300 years (GJ)				600211.99	Total heat removed from 100 to 300 years (GJ)			309870.00
Percentage of total heat removal in 25 years = 80%								
Percentage of total heat removal in 50 years = 83%								
Percentage of total heat removal from 50 to 100 years = 59%								
Percentage of total heat removal from 100 to 300 years = 52%								

Source: DTN: MO0107MWDTEM05.011



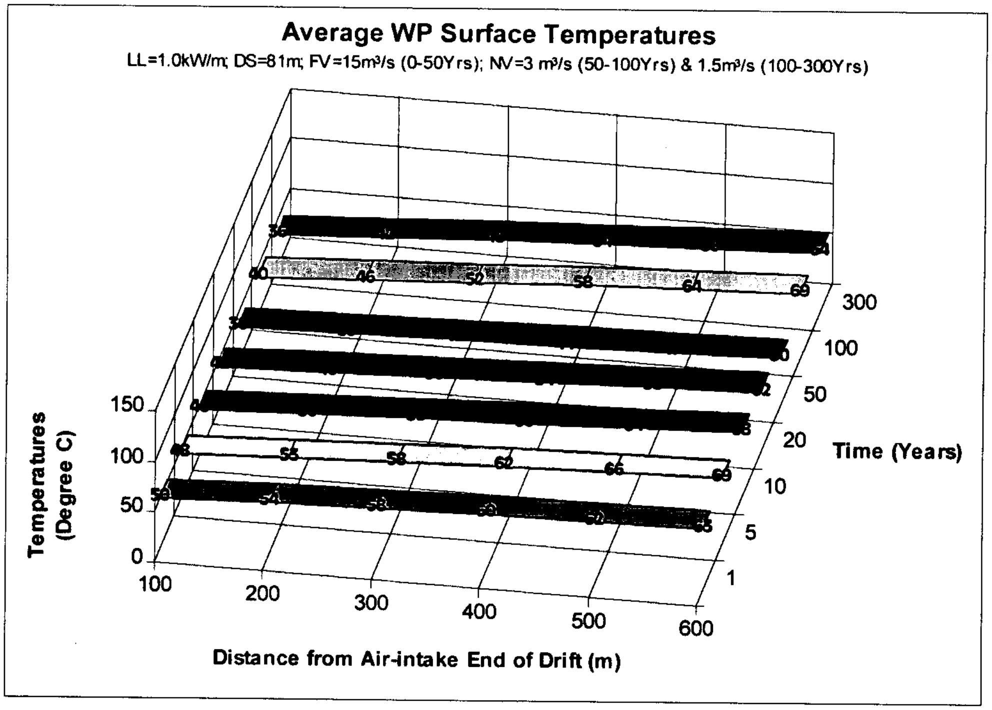
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-1. Average Drift Wall Temperatures for Representative Scenario



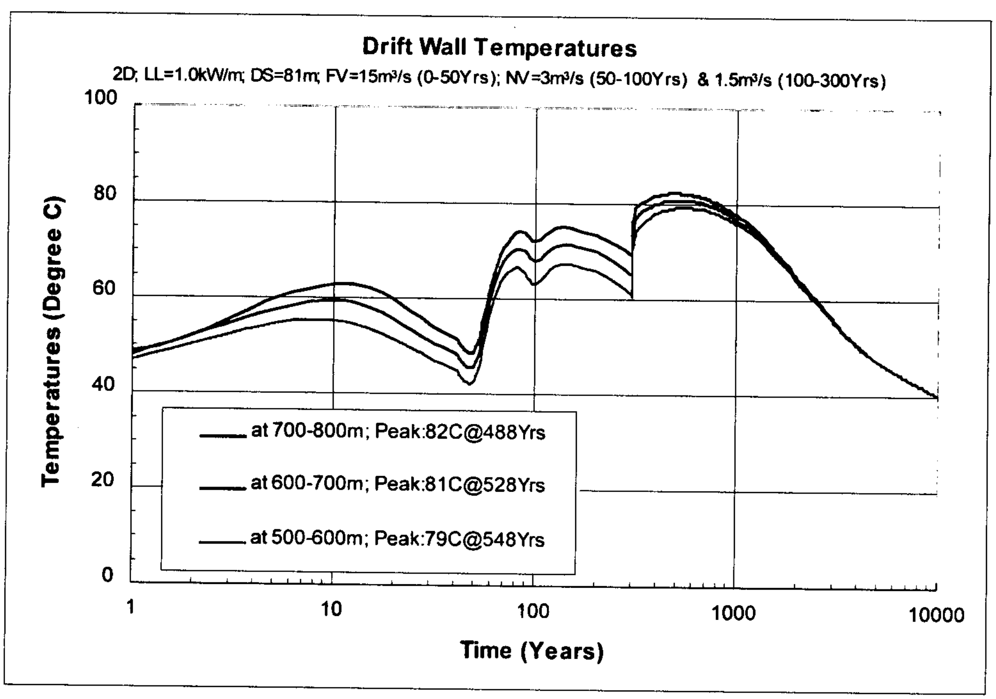
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-2. Average Air Temperatures for Representative Scenario



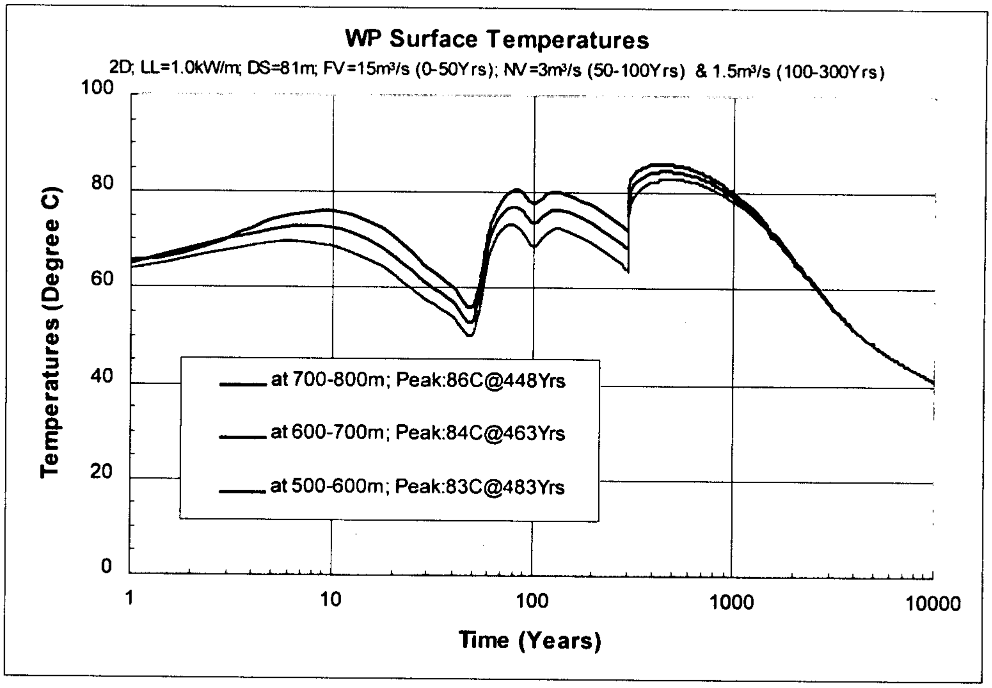
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-3. Average Waste Package Surface Temperatures for Representative Scenario



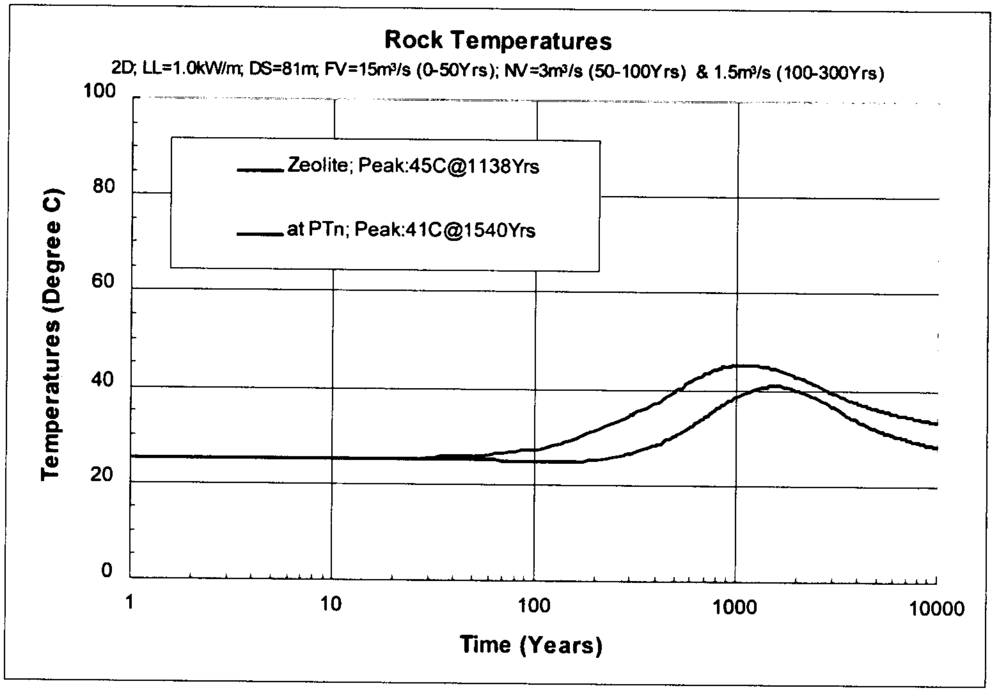
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-4. Drift Wall Temperatures for Representative Scenario



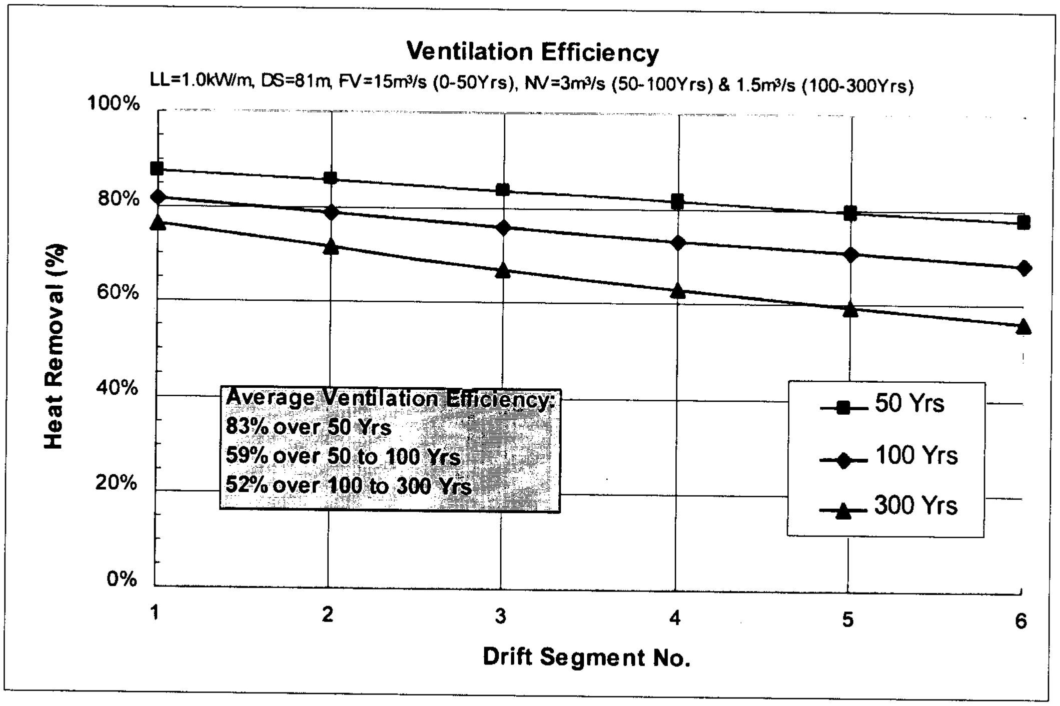
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-5. WP Surface Temperatures for Representative Scenario



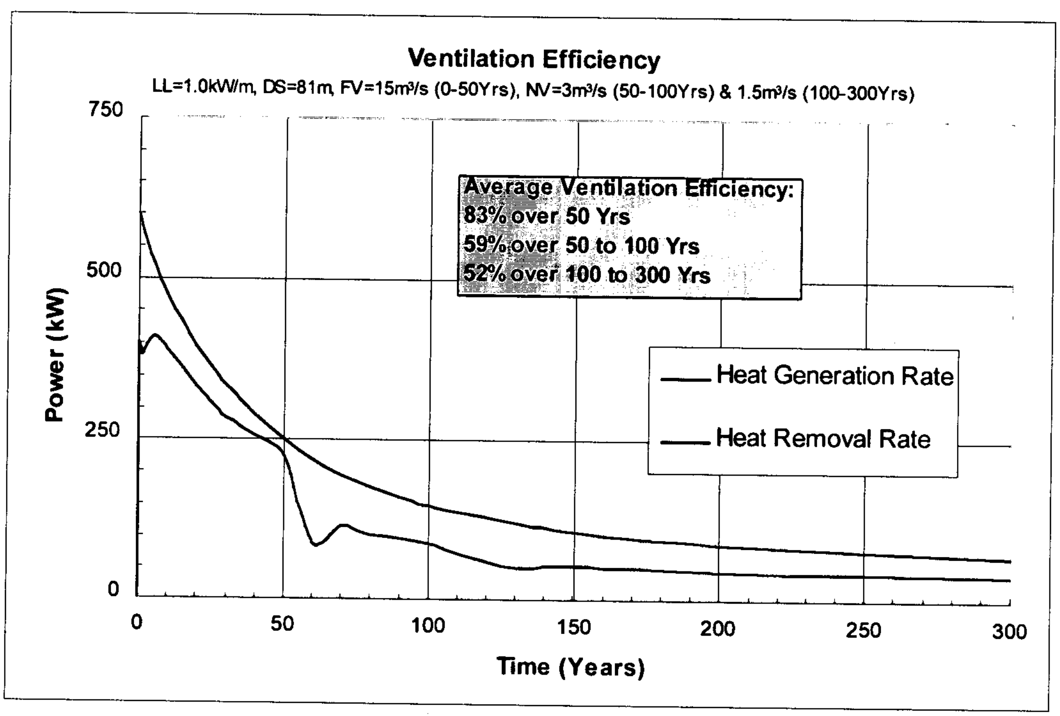
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-6. Rock Temperatures at Zeolite and PTn Unit for Representative Scenario



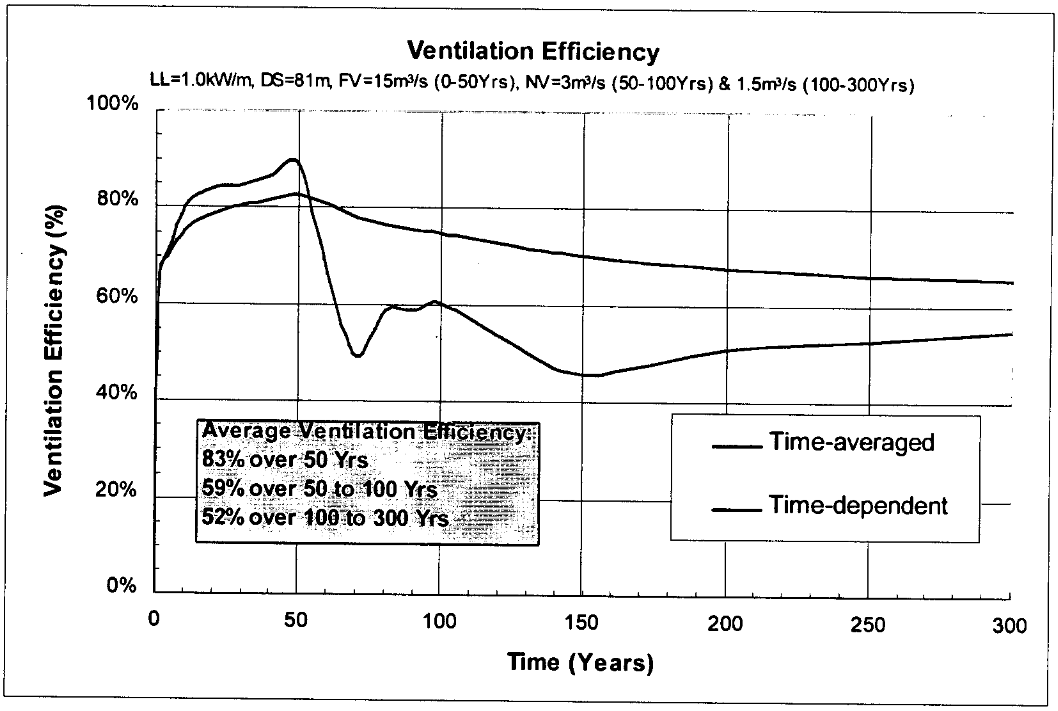
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-7. Average Heat Removal Rates at Different Drift Segments for Representative Scenario



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-8. Overall Heat Generation and Removal Rates at Different Time for Representative Scenario



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure III-9. Time-averaged and Time-dependent Ventilation Efficiencies for Representative Scenario

ATTACHMENT IV

TEMPERATURES AND VENTILATION EFFICIENCY FOR ALTERNATIVE SCENARIO TWO

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 1.45 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 300 years. The drift spacing for this case is 120 m. This represents *Alternative Scenario Two* for low temperature repository design. Ventilation efficiency is calculated for up to 300 years. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table IV-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m, 15 m^3/s (0-300 Years), and 120-m drift spacing (Alternative Scenario Two)

Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.91	25.91	25.91	25.91	25.91
1.0	37.41	43.76	48.28	51.55	53.93	55.65
5.0	36.38	44.37	51.69	58.10	63.56	68.11
10.0	35.32	42.70	50.01	57.11	63.83	70.05
15.0	34.37	41.12	47.85	54.54	61.16	67.62
20.0	33.59	39.78	45.96	52.13	58.28	64.40
25.0	32.87	38.56	44.25	49.94	55.61	61.28
30.0	32.26	37.51	42.76	48.00	53.26	58.50
40.0	31.21	35.89	40.62	45.38	50.18	54.99
50.0	30.39	34.45	38.59	42.80	47.06	51.38
60.0	29.73	33.29	36.91	40.60	44.36	48.17
70.0	29.20	32.35	35.55	38.81	42.13	45.50
80.0	28.77	31.58	34.45	37.36	40.31	43.31
90.0	28.42	30.97	33.55	36.17	38.84	41.53
100.0	28.14	30.47	32.83	35.22	37.63	40.08
125.0	27.72	29.80	31.92	34.07	36.27	38.48
150.0	27.30	29.09	30.93	32.83	34.77	36.75
200.0	26.90	28.41	29.97	31.58	33.26	34.98
250.0	26.67	27.95	29.28	30.66	32.09	33.56
300.0	26.51	27.66	28.83	30.03	31.27	32.55

Source: DTN: MO0107MWDTEM05.011

Table IV-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m, 15 m^3/s (0-300 Years), and 120-m drift spacing (Alternative Scenario Two)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.01	30.03	30.03	30.03	30.03	30.03
1.0	31.83	36.84	40.46	43.09	44.99	46.37
5.0	33.31	40.97	47.71	53.46	58.26	62.21
10.0	32.59	40.14	47.50	54.49	60.98	66.87
15.0	31.91	38.82	45.71	52.54	59.23	65.69
20.0	31.32	37.65	43.99	50.31	56.61	62.85
25.0	30.81	36.63	42.46	48.28	54.10	59.91
30.0	30.36	35.72	41.09	46.47	51.85	57.22
40.0	29.78	34.62	39.49	44.40	49.33	54.27
50.0	29.14	33.36	37.66	42.02	46.44	50.90
60.0	28.62	32.31	36.08	39.91	43.81	47.77
70.0	28.20	31.46	34.78	38.16	41.60	45.10
80.0	27.86	30.77	33.73	36.74	39.79	42.90
90.0	27.59	30.21	32.87	35.58	38.32	41.10
100.0	27.36	29.76	32.18	34.63	37.12	39.64
125.0	27.11	29.26	31.45	33.68	35.93	38.22
150.0	26.81	28.68	30.60	32.57	34.58	36.62
200.0	26.52	28.10	29.73	31.43	33.17	34.96
250.0	26.29	27.63	29.02	30.46	31.95	33.49
300.0	26.15	27.33	28.54	29.79	31.08	32.41

Source: DTN: MO0107MWDTEM05.011

Table IV-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 1.45 kW/m, 15 m^3/s (0-300 Years), and 120-m drift spacing (Alternative Scenario Two)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.96	67.03	67.03	67.03	67.03	67.03
1.0	60.04	65.75	69.82	72.78	74.94	76.50
5.0	57.23	64.39	70.99	76.81	81.77	85.92
10.0	54.36	61.02	67.65	74.12	80.27	85.99
15.0	51.88	58.01	64.15	70.28	76.37	82.33
20.0	49.80	55.46	61.14	66.83	72.51	78.18
25.0	47.86	53.10	58.36	63.63	68.91	74.18
30.0	46.20	51.07	55.94	60.83	65.73	70.64
40.0	43.30	47.69	52.14	56.62	61.13	65.67
50.0	41.02	44.86	48.77	52.76	56.81	60.91
60.0	39.15	42.53	45.98	49.50	53.08	56.73
70.0	37.62	40.63	43.70	46.82	50.00	53.24
80.0	36.37	39.08	41.83	44.63	47.48	50.36
90.0	35.35	37.81	40.30	42.83	45.41	48.01
100.0	34.52	36.77	39.06	41.37	43.71	46.08
125.0	33.27	35.29	37.35	39.45	41.59	43.74
150.0	32.01	33.76	35.56	37.41	39.31	41.25
200.0	30.81	32.28	33.82	35.40	37.04	38.73
250.0	30.11	31.36	32.67	34.02	35.43	36.88
300.0	29.62	30.74	31.89	33.08	34.30	35.56

Source: DTN: MO0107MWDTEM05.011

Table IV-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 1.45 kW/m, 15 m^3/s (0-300 Years), and 120-m drift spacing (Alternative Scenario Two)

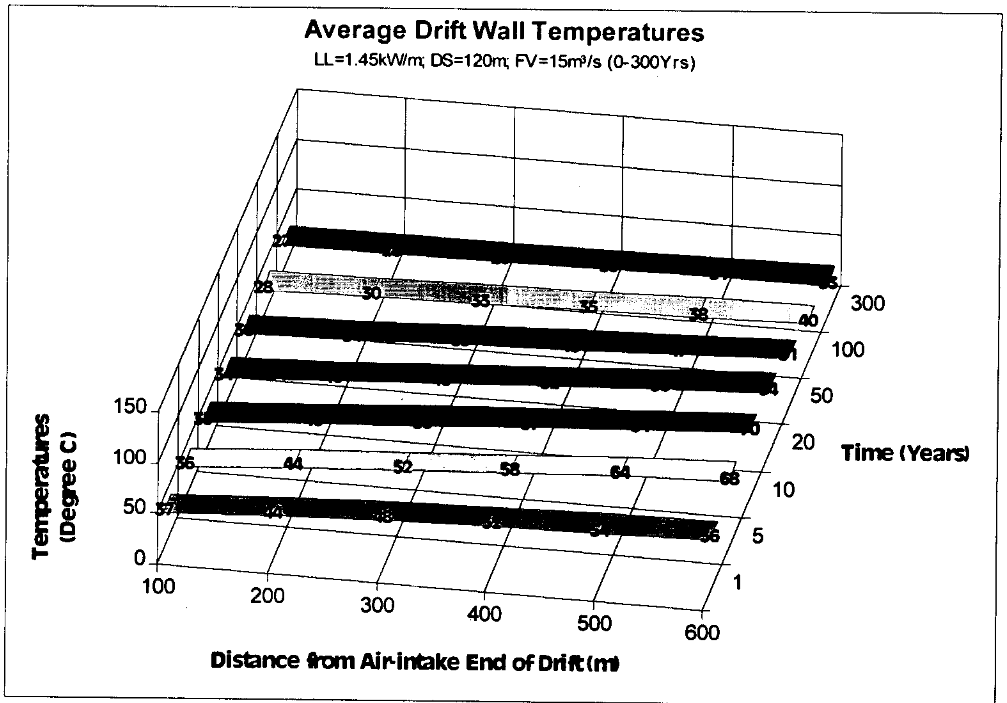
Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.67	66.95	66.95	66.95	66.95	66.95
1.0	90.87	84.56	79.30	75.52	72.81	70.82
5.0	110.56	105.86	100.49	95.54	91.16	87.36
10.0	101.01	98.60	95.72	92.49	89.01	85.49
15.0	91.91	90.16	88.27	86.18	83.87	81.36
20.0	84.15	82.69	81.18	79.61	77.92	76.13
25.0	77.34	76.08	74.81	73.54	72.13	70.71
30.0	71.26	70.20	69.08	67.96	66.78	65.59
40.0	63.64	62.84	61.98	61.04	60.12	59.14
50.0	55.03	54.50	53.91	53.24	52.54	51.80
60.0	48.17	47.77	47.31	46.86	46.33	45.79
70.0	42.62	42.27	41.92	41.58	41.17	40.76
80.0	38.11	37.81	37.52	37.24	36.93	36.58
90.0	34.44	34.20	33.94	33.70	33.47	33.16
100.0	31.47	31.25	31.05	30.81	30.61	30.37
125.0	28.12	27.96	27.83	27.65	27.49	27.29
150.0	24.12	24.06	24.00	23.92	23.84	23.69
200.0	20.22	20.23	20.25	20.22	20.23	20.16
250.0	17.21	17.23	17.26	17.26	17.31	17.29
300.0	15.33	15.32	15.34	15.35	15.39	15.40

Source: DTN: MO0107MWDTEM05.011

Table IV-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 1.45 kW/m, 15 m^3/s (0-300 Years), and 120-m drift spacing (Alternative Scenario Two)

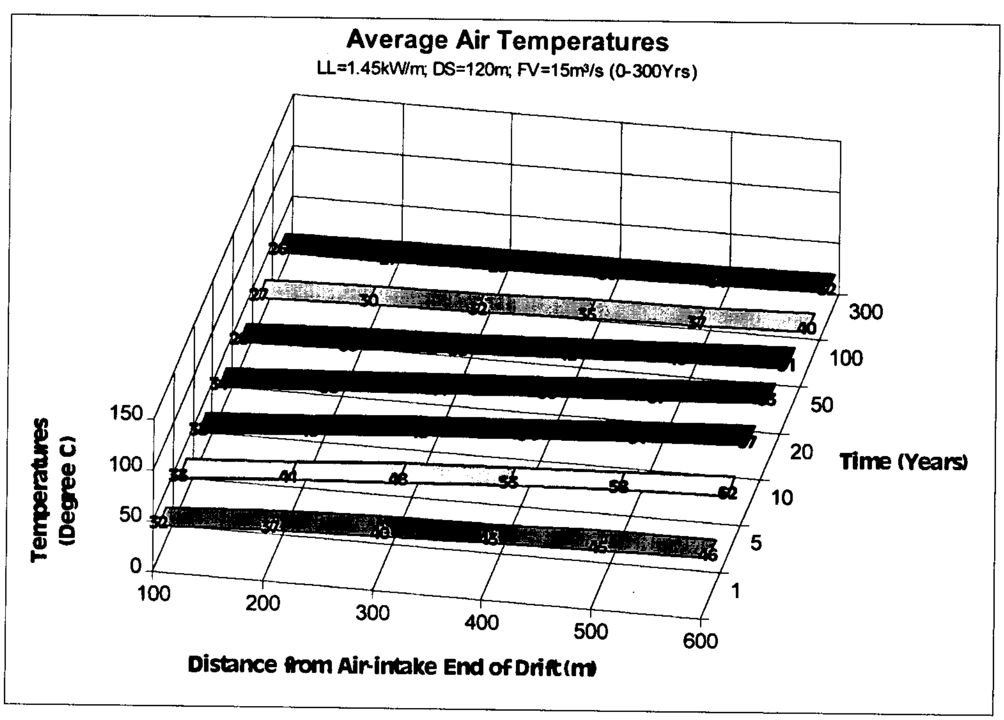
Time (years)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (years)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	870.00	870.00	2.74	1.00E-04	401.40	200.70	0.63
1.0	96.74%	841.63	855.82	26986.34	1.0	473.88	437.64	13800.11
5.0	87.38%	760.22	800.93	101031.99	5.0	590.97	532.43	67162.36
10.0	78.86%	686.11	723.17	114028.75	10.0	562.32	576.65	90925.61
15.0	71.87%	625.27	655.69	103389.54	15.0	521.75	542.04	85468.39
20.0	65.83%	572.71	598.99	94448.98	20.0	481.67	501.71	79109.97
25.0	60.52%	526.49	549.60	86660.82	25.0	444.61	463.14	73028.07
30.0	55.82%	485.65	506.07	79796.67	30.0	410.88	427.74	67446.64
40.0	47.95%	417.15	451.40	142352.80	40.0	368.76	389.82	122933.75
50.0	41.66%	362.42	389.78	122922.17	50.0	321.02	344.89	108764.24
60.0	36.62%	318.62	340.52	107386.87	60.0	282.24	301.63	95121.36
70.0	32.56%	283.25	300.94	94903.41	70.0	250.31	266.27	83972.45
80.0	29.26%	254.56	268.90	84801.55	80.0	224.20	237.26	74820.76
90.0	26.57%	231.14	242.85	76584.99	90.0	202.91	213.56	67347.32
100.0	24.38%	212.12	221.63	69893.78	100.0	185.56	194.23	61253.94
125.0	21.09%	183.51	197.82	155957.83	125.0	166.34	175.95	138717.40
150.0	17.80%	154.89	169.20	133398.33	150.0	143.63	154.99	122191.49
200.0	14.70%	127.92	141.41	222968.18	200.0	121.31	132.47	208878.86
250.0	12.91%	112.36	120.14	189434.61	250.0	103.57	112.44	177292.42
300.0	11.66%	101.42	106.89	168548.44	300.0	92.14	97.86	154297.89
Total heat generated in 25 years (GJ)				526549.17	Total heat removed in 25 years (GJ)			409495.14
Total heat generated in 50 years (GJ)				871620.81	Total heat removed in 50 years (GJ)			708639.77
Total heat generated in 100 years (GJ)				1305191.42	Total heat removed in 100 years (GJ)			1091155.60
Total heat generated in 300 years (GJ)				2175498.80	Total heat removed in 300 years (GJ)			1892533.66
Percentage of total heat removal in 25 years = 78%								
Percentage of total heat removal in 50 years = 81%								
Percentage of total heat removal in 100 years = 84%								
Percentage of total heat removal in 300 years = 87%								

Source: DTN: MO0107MWDTEM05.011



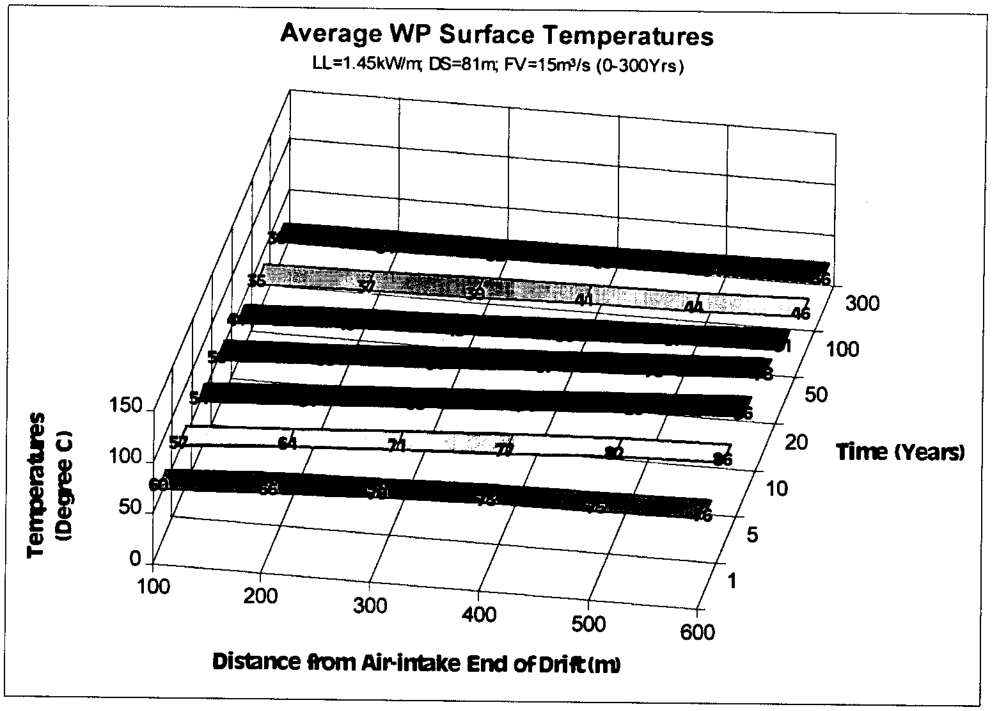
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure IV-1. Average Drift Wall Temperatures for Alternative Scenario Two



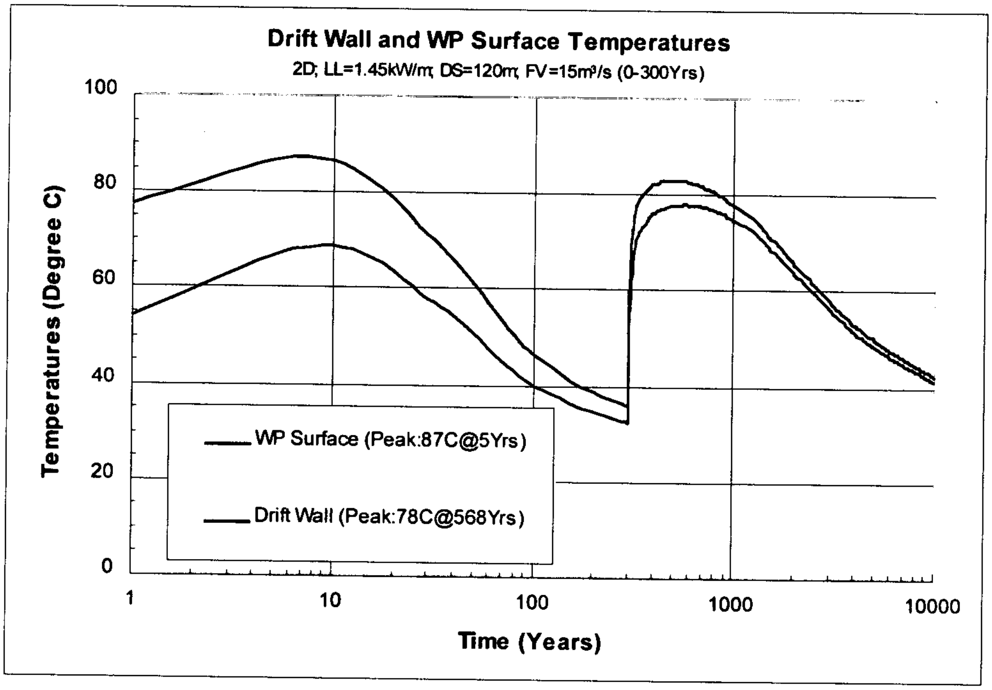
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure IV-2. Average Air Temperatures for Alternative Scenario Two



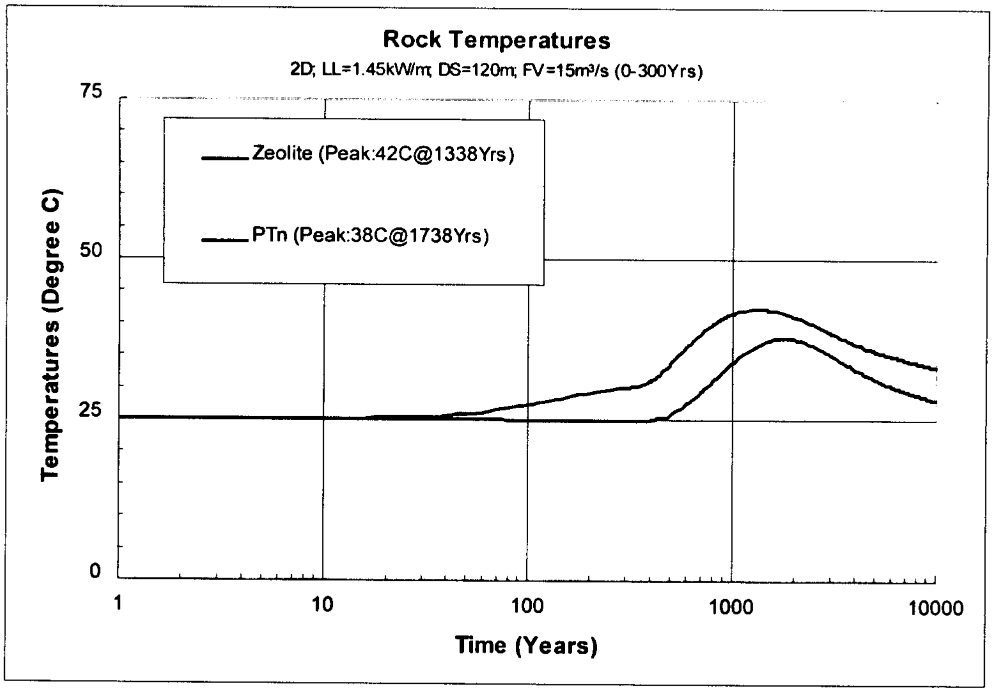
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure IV-3. Average Waste Package Surface Temperatures for Alternative Scenario Two



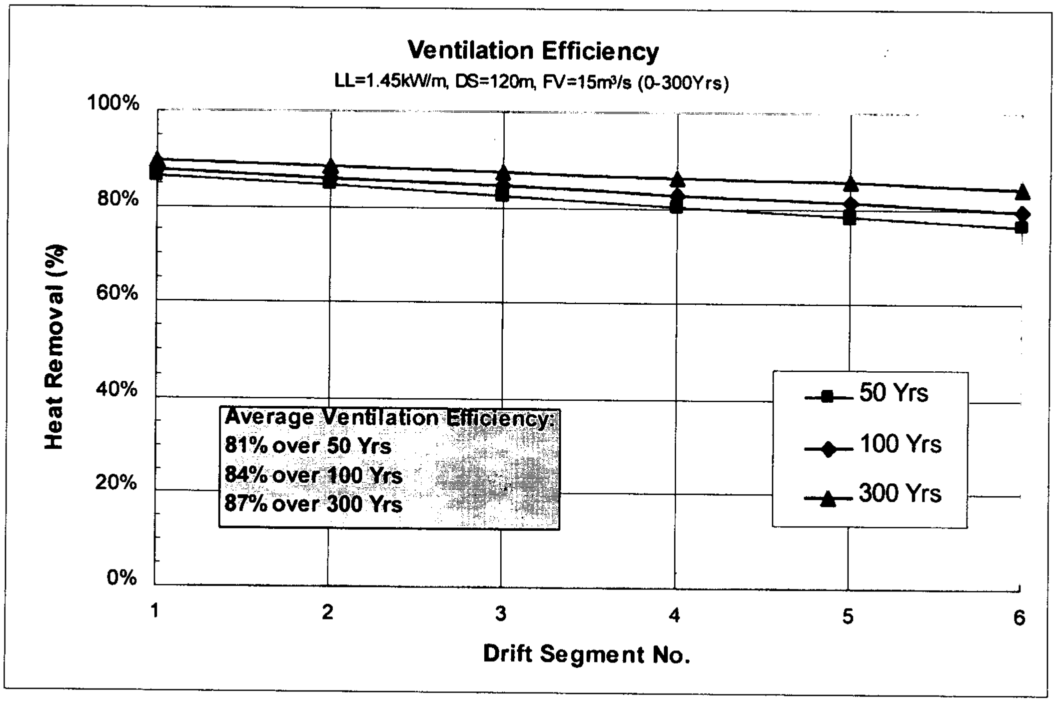
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure IV-4. Drift Wall and WP Surface Temperatures for Alternative Scenario Two



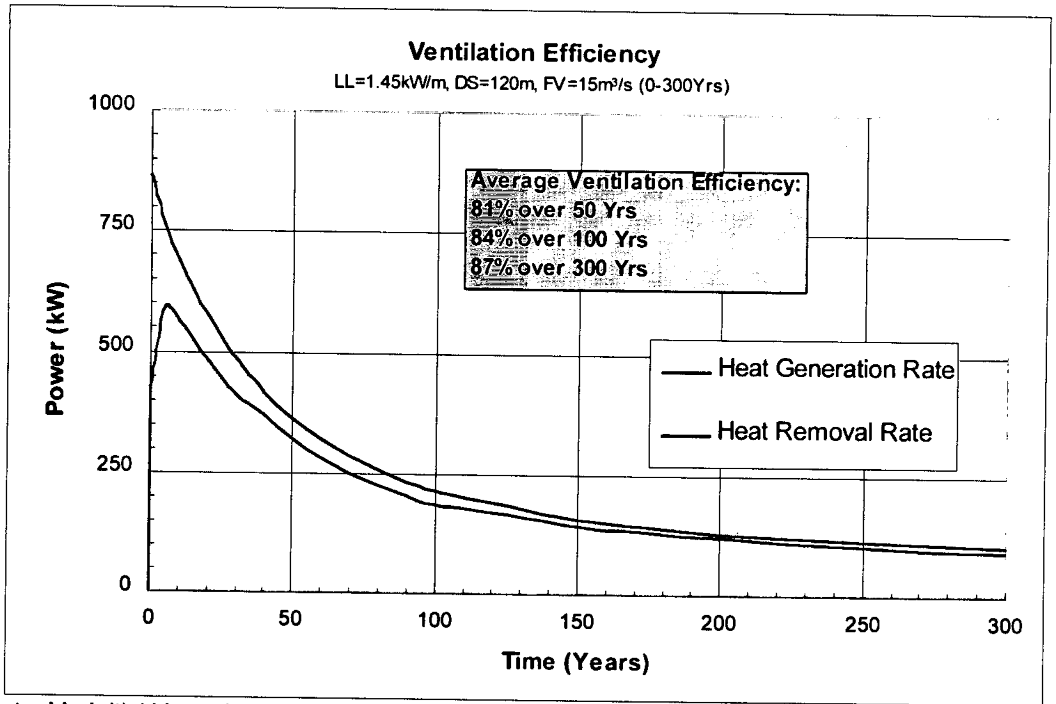
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure IV-5. Rock Temperatures at Zeolite and PTn Unit for Alternative Scenario Two



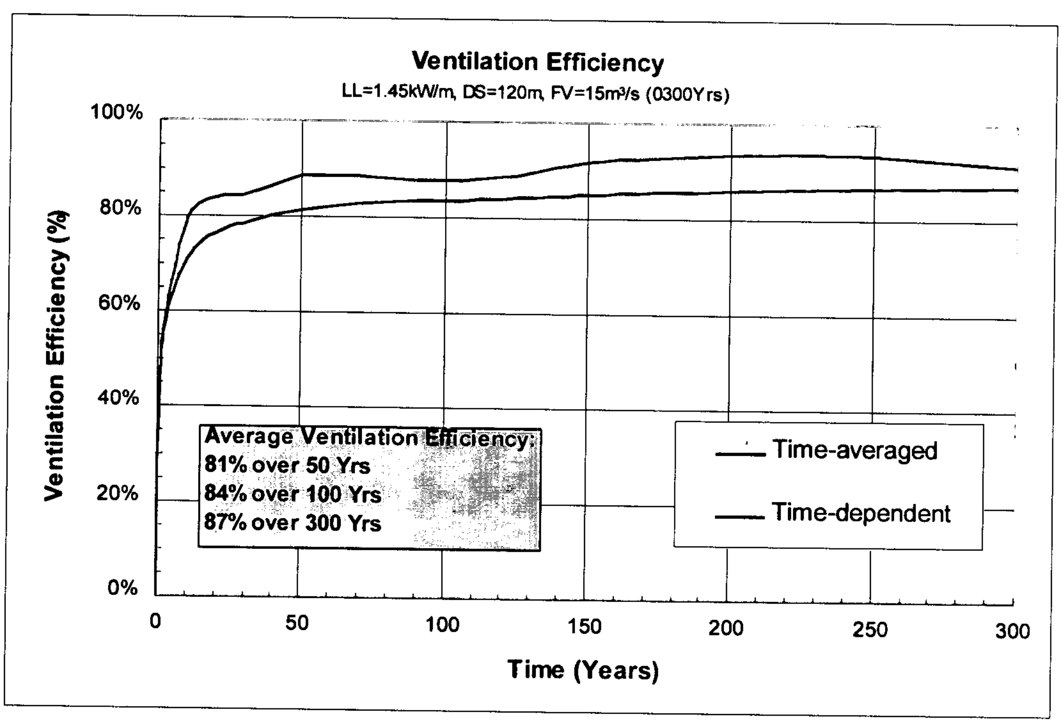
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure IV-6. Average Heat Removal Rates at Different Drift Segments for Alternative Scenario Two



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure IV-7. Overall Heat Generation and Removal Rates at Different Time for Alternative Scenario Two



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure IV-8. Time-averaged and Time-dependent Ventilation Efficiencies for Alternative Scenario Two

ATTACHMENT V

TEMPERATURES AND VENTILATION EFFICIENCY FOR ALTERNATIVE SCENARIO THREE

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 0.7 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 125 years. The drift spacing for this case is 81 m. This represents *Alternative Scenario Three* for low temperature repository design. Ventilation efficiency is calculated for up to 125 years. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table V-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 0.7 kW/m, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Three)

Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.90	25.90	25.90	25.90	25.90
1.0	30.88	35.15	38.19	40.38	41.97	43.13
5.0	30.31	34.16	37.97	41.48	44.57	47.21
10.0	29.84	33.36	36.88	40.37	43.76	46.99
15.0	29.41	32.64	35.86	39.09	42.29	45.47
20.0	29.04	32.00	34.97	37.93	40.90	43.85
25.0	28.72	31.44	34.17	36.90	39.64	42.38
30.0	28.43	30.95	33.47	36.00	38.53	41.06
40.0	27.95	30.21	32.49	34.80	37.11	39.43
50.0	27.57	29.53	31.53	33.58	35.64	37.75
60.0	27.26	28.98	30.74	32.53	34.36	36.23
70.0	27.01	28.54	30.09	31.68	33.30	34.95
80.0	26.81	28.18	29.57	30.99	32.44	33.91
90.0	26.64	27.88	29.14	30.43	31.73	33.06
100.0	26.51	27.65	28.80	29.96	31.16	32.37
125.0	26.31	27.32	28.36	29.42	30.49	31.59

Source: DTN: MO0107MWDTEM05.011

Table V-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 0.7 kW/m, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Three)

Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.00	30.02	30.02	30.02	30.02	30.02
1.0	29.59	32.98	35.44	37.22	38.51	39.44
5.0	29.02	33.03	36.74	40.02	42.82	45.16
10.0	28.66	32.31	35.95	39.50	42.89	46.04
15.0	28.33	31.67	35.01	38.34	41.65	44.89
20.0	28.05	31.11	34.17	37.24	40.30	43.35
25.0	27.80	30.61	33.43	36.25	39.08	41.90
30.0	27.59	30.18	32.78	35.38	37.99	40.61
40.0	27.31	29.65	32.02	34.40	36.79	39.19
50.0	27.00	29.05	31.14	33.26	35.42	37.59
60.0	26.75	28.54	30.37	32.24	34.15	36.09
70.0	26.55	28.13	29.75	31.40	33.08	34.80
80.0	26.39	27.80	29.24	30.71	32.21	33.74
90.0	26.25	27.53	28.83	30.15	31.50	32.87
100.0	26.15	27.31	28.49	29.70	30.92	32.16
125.0	26.02	27.07	28.14	29.23	30.34	31.47

Source: DTN: MO0107MWDTEM05.011

Table V-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 0.7 kW/m, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Three)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.80	66.87	66.87	66.87	66.87	66.87
1.0	42.50	46.58	49.54	51.64	53.18	54.30
5.0	41.08	44.75	48.39	51.75	54.71	57.24
10.0	39.63	43.00	46.36	49.70	52.96	56.07
15.0	38.39	41.48	44.57	47.67	50.75	53.82
20.0	37.29	40.14	42.99	45.85	48.71	51.56
25.0	36.33	38.95	41.59	44.23	46.88	49.53
30.0	35.47	37.91	40.35	42.80	45.25	47.71
40.0	34.04	36.23	38.45	40.70	42.95	45.22
50.0	32.88	34.79	36.75	38.75	40.77	42.83
60.0	31.95	33.63	35.35	37.11	38.90	40.73
70.0	31.19	32.68	34.21	35.77	37.36	38.98
80.0	30.57	31.92	33.28	34.68	36.10	37.55
90.0	30.06	31.28	32.52	33.79	35.07	36.38
100.0	29.65	30.77	31.91	33.06	34.23	35.42
125.0	29.03	30.03	31.05	32.10	33.16	34.25

Source: DTN: MO0107MWDTEM05.011

Table V-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 0.7 kW/m, 15 m^3/s (0-125 Years), and 81-m drift spacing (Scenario IV)

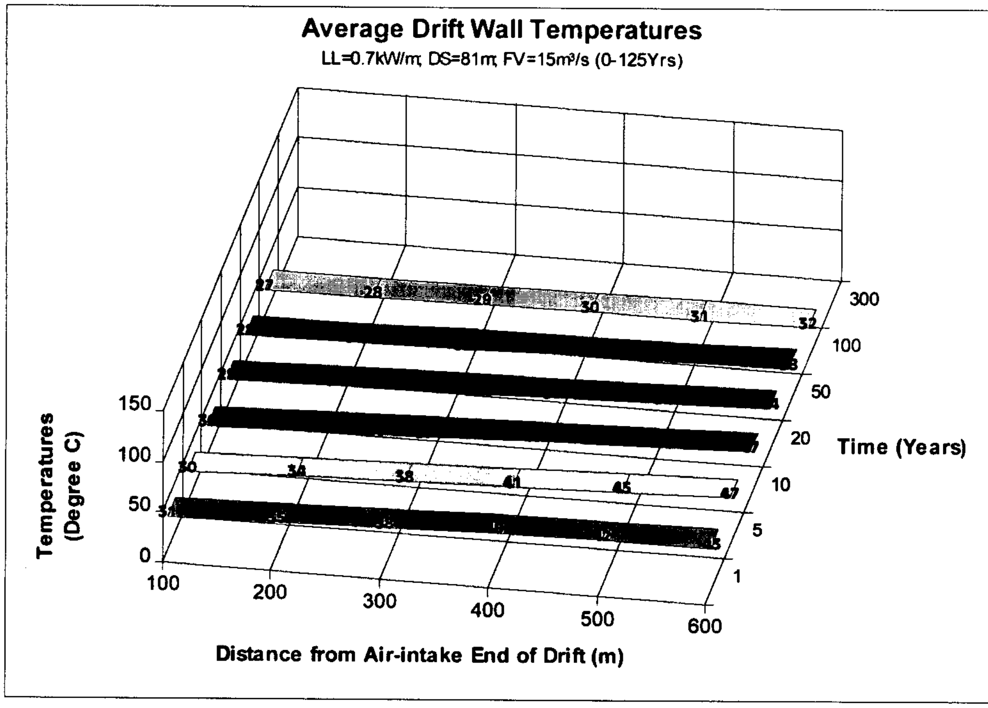
Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.55	66.82	66.82	66.82	66.82	66.82
1.0	61.09	57.13	53.66	51.10	49.26	47.93
5.0	53.44	51.96	49.51	46.97	44.64	42.53
10.0	48.65	47.68	46.53	45.21	43.71	42.09
15.0	44.37	43.58	42.74	41.87	40.89	39.86
20.0	40.61	39.94	39.28	38.57	37.85	37.09
25.0	37.31	36.74	36.18	35.60	35.01	34.39
30.0	34.41	33.94	33.44	32.96	32.42	31.92
40.0	30.75	30.43	30.05	29.69	29.25	28.82
50.0	26.64	26.43	26.20	25.97	25.66	25.36
60.0	23.32	23.17	23.02	22.86	22.66	22.49
70.0	20.64	20.53	20.41	20.31	20.18	20.05
80.0	18.46	18.39	18.29	18.22	18.13	18.03
90.0	16.69	16.63	16.57	16.51	16.44	16.38
100.0	15.25	15.21	15.16	15.11	15.08	15.02
125.0	13.63	13.62	13.59	13.56	13.55	13.50

Source: DTN: MO0107MWDTEM05.011

Table V-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 0.7 kW/m, 15 m^3/s (0-125 Years), and 81-m drift spacing (Scenario IV)

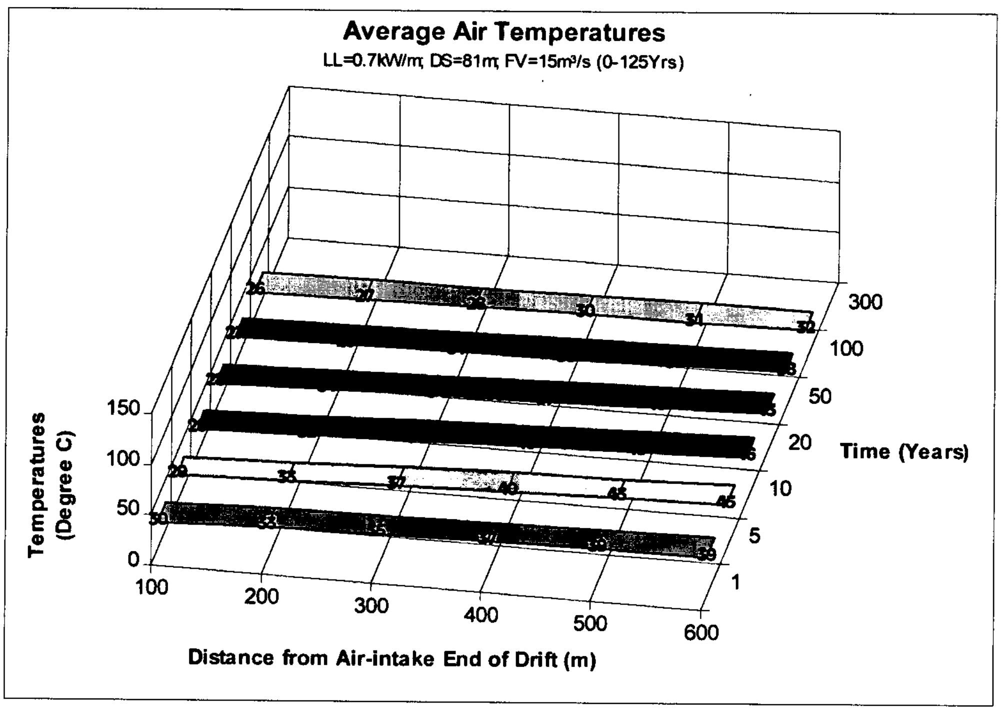
Time (years)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (years)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	420.00	420.00	1.32	1.00E-04	400.67	200.33	0.63
1.0	96.74%	406.31	413.15	13027.89	1.0	320.18	360.42	11365.11
5.0	87.38%	367.00	386.65	48774.06	5.0	289.03	304.60	38424.08
10.0	78.86%	331.23	349.11	55048.36	10.0	273.86	281.45	44378.41
15.0	71.87%	301.85	316.54	49912.19	15.0	253.30	263.58	41561.51
20.0	65.83%	276.48	289.17	45596.06	20.0	233.34	243.32	38367.16
25.0	60.52%	254.17	265.32	41836.26	25.0	215.23	224.28	35365.09
30.0	55.82%	234.45	244.31	38522.53	30.0	199.08	207.15	32663.66
40.0	47.95%	201.38	217.92	68722.04	40.0	179.00	189.04	59614.90
50.0	41.66%	174.96	188.17	59341.74	50.0	156.27	167.63	52864.76
60.0	36.62%	153.82	164.39	51841.94	60.0	137.53	146.90	46325.63
70.0	32.56%	136.74	145.28	45815.44	70.0	122.11	129.82	40940.24
80.0	29.26%	122.89	129.82	40938.68	80.0	109.53	115.82	36525.03
90.0	26.57%	111.59	117.24	36972.06	90.0	99.22	104.37	32915.40
100.0	24.38%	102.40	106.99	33741.83	100.0	90.83	95.03	29967.31
125.0	21.09%	88.59	95.50	75289.99	125.0	81.45	86.14	67911.30
Total heat generated in 25 years (GJ)				254196.15	Total heat removed in 25 years (GJ)			209461.99
Total heat generated in 50 years (GJ)				420782.46	Total heat removed in 50 years (GJ)			354605.31
Total heat generated in 100 years (GJ)				630092.41	Total heat removed in 100 years (GJ)			541278.92
Total heat generated in 125 years (GJ)				705382.39	Total heat removed in 125 years (GJ)			609190.22
Percentage of total heat removal in 25 years = 82%								
Percentage of total heat removal in 50 years = 84%								
Percentage of total heat removal in 100 years = 86%								
Percentage of total heat removal in 125 years = 86%								

Source: DTN: MO0107MWDTEM05.011



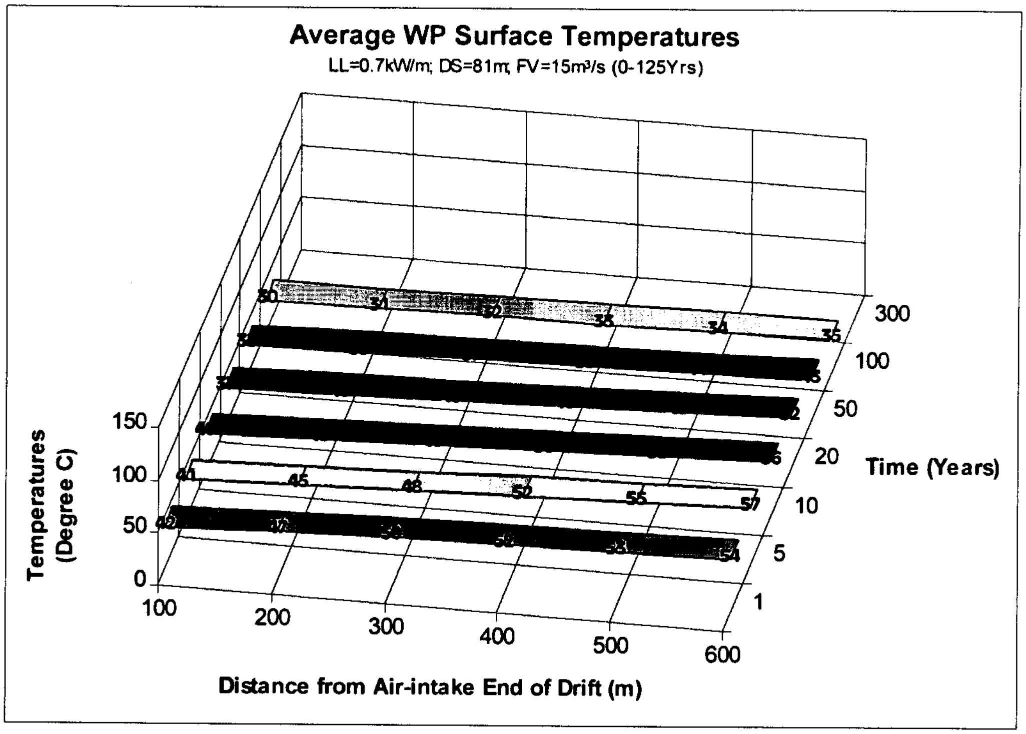
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure V-1. Average Drift Wall Temperatures for Alternative Scenario Three



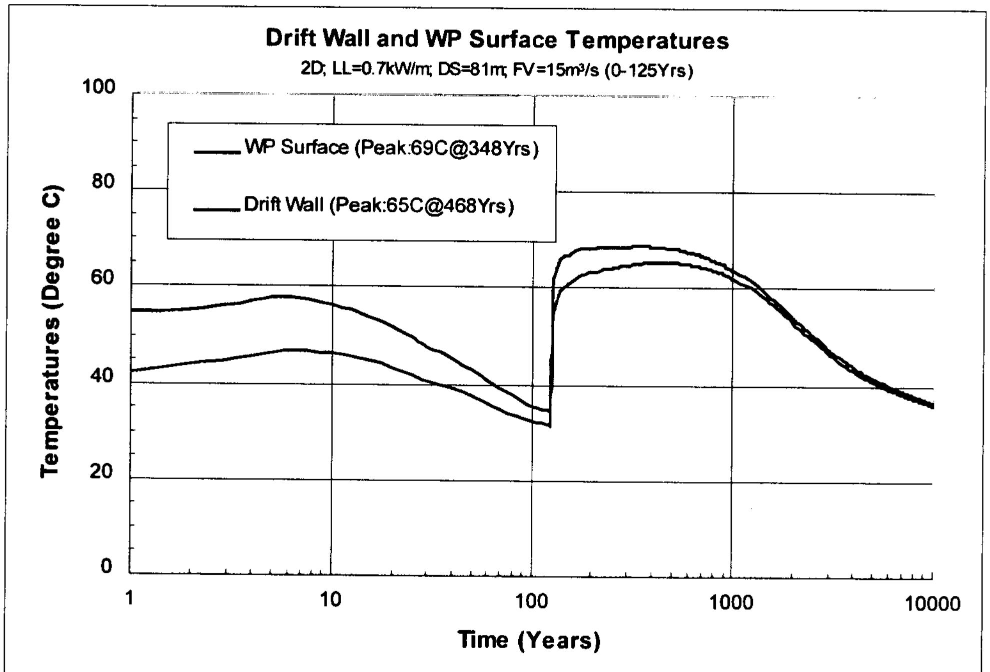
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure V-2. Average Air Temperatures for Alternative Scenario Three



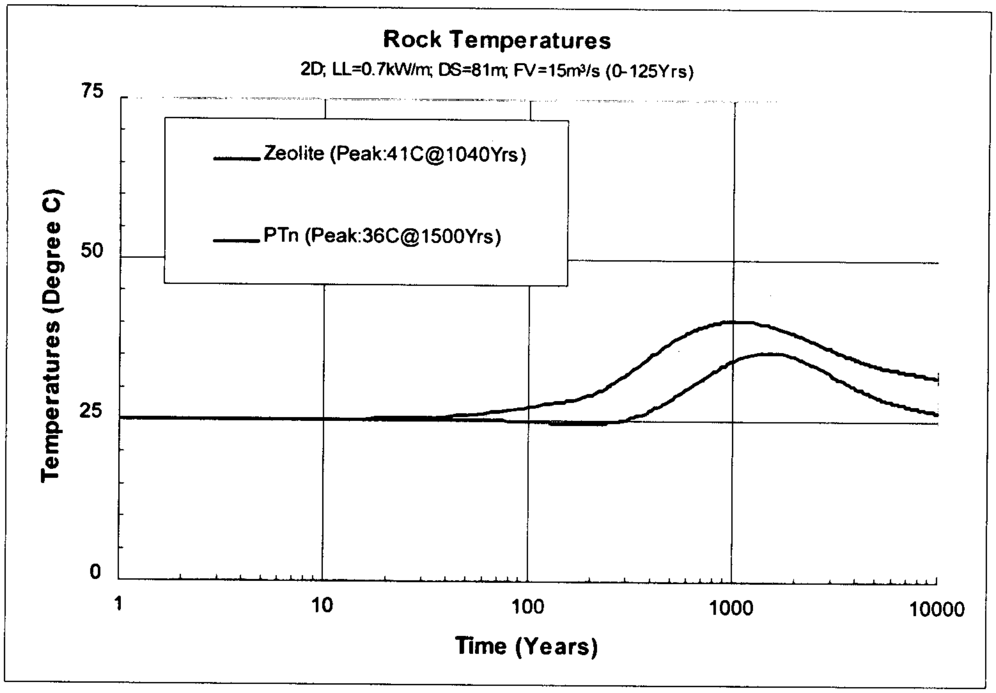
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure V-3. Average Waste Package Surface Temperatures for Alternative Scenario Three



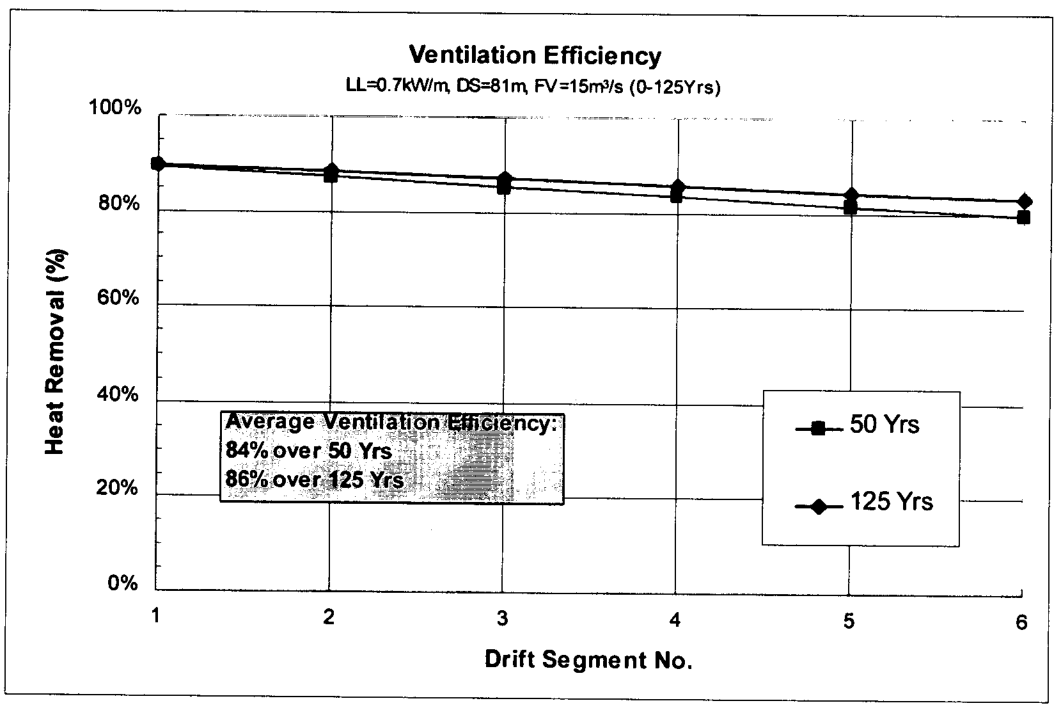
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure V-4. Drift Wall and WP Surface Temperatures for Alternative Scenario Three



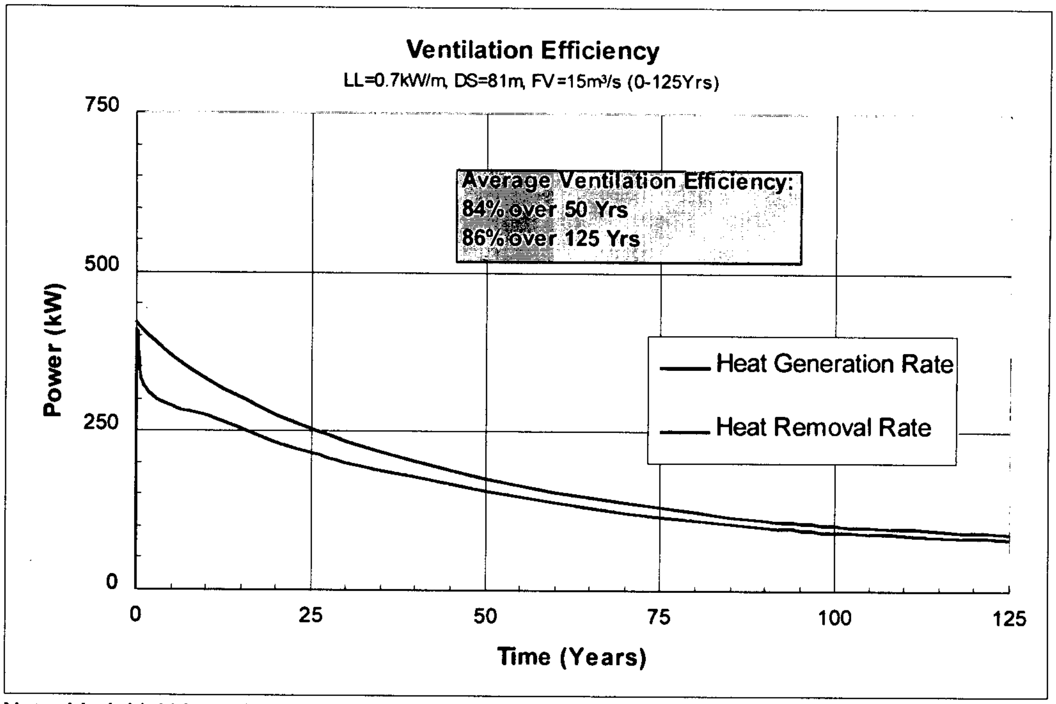
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure V-5. Rock Temperatures at Zeolite and PTn Unit for Alternative Scenario Three



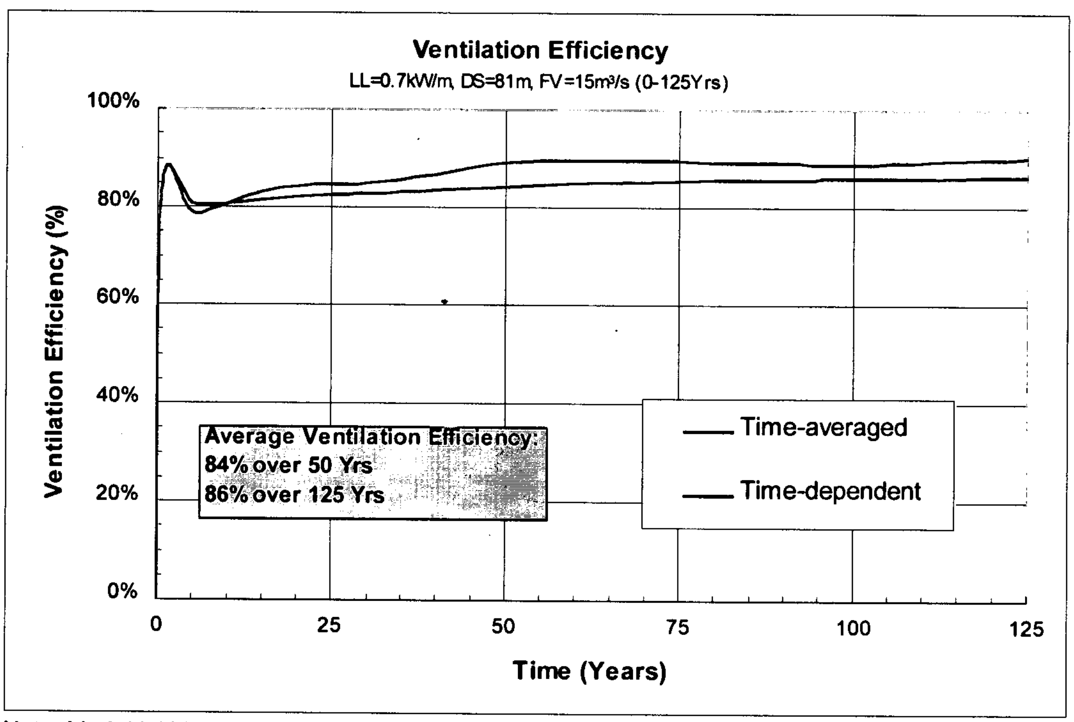
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure V-6. Average Heat Removal Rates at Different Drift Segments for Alternative Scenario Three



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure V-7. Overall Heat Generation and Removal Rates at Different Time for Alternative Scenario Three



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure V-8. Time-averaged and Time-dependent Ventilation Efficiencies for Alternative Scenario Three

ATTACHMENT VI

TEMPERATURES AND VENTILATION EFFICIENCY FOR ALTERNATIVE SCENARIO FOUR

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 0.6 kW/m by Additional 30 years of aging with a forced ventilation air flow rate of 15 m^3/s from 0 to 125 years. The drift spacing for this case is 81 m. This represents *Alternative Scenario Four* for low temperature repository design. Ventilation efficiency is calculated for up to 125 years. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table VI-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 0.6 kW/m by Additional 30 Years of Aging, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Four)

Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.90	25.90	25.90	25.90	25.90
5.0	29.52	33.44	36.30	38.40	39.95	41.16
10.0	29.18	32.21	35.35	38.33	41.01	43.47
15.0	28.90	31.73	34.54	37.36	40.14	42.95
20.0	28.65	31.29	33.93	36.54	39.14	41.85
25.0	28.41	30.90	33.37	35.83	38.27	40.83
30.0	28.21	30.54	32.87	35.19	37.49	39.89
40.0	27.85	30.00	32.15	34.30	36.46	38.70
50.0	27.57	29.49	31.44	33.40	35.38	37.45
60.0	27.34	29.08	30.84	32.63	34.42	36.31
70.0	27.15	28.75	30.35	31.98	33.62	35.34
95.0	26.86	28.28	29.75	31.22	32.71	34.26
125.0	26.57	27.80	29.06	30.36	31.69	33.02

Source: DTN: MO0107MWDTEM05.011

Table VI-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 0.6 kW/m by Additional 30 Years of Aging, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Four)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.00	30.02	30.02	30.02	30.02	30.02
5.0	29.11	32.17	34.42	36.07	37.29	38.20
10.0	28.13	31.42	34.56	37.39	39.86	42.02
15.0	27.92	30.84	33.77	36.68	39.49	42.21
20.0	27.73	30.46	33.17	35.87	38.56	41.28
25.0	27.56	30.11	32.65	35.18	37.70	40.27
30.0	27.40	29.80	32.19	34.57	36.94	39.36
40.0	27.20	29.41	31.63	33.85	36.07	38.34
50.0	26.97	28.96	30.98	33.01	35.05	37.15
60.0	26.78	28.58	30.41	32.25	34.11	36.03
70.0	26.63	28.27	29.93	31.61	33.31	35.06
95.0	26.45	27.94	29.44	30.96	32.50	34.09
125.0	26.25	27.53	28.85	30.20	31.58	32.98

Source: DTN: MO0107MWDTEM05.011

Table VI-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 0.6 kW/m by Additional 30 Years of Aging, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Four)

Time (Years)	**Location Measured from Air-intake End (m)**					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.77	66.84	66.84	66.84	66.84	66.84
5.0	38.56	42.35	45.12	47.17	48.66	49.91
10.0	37.77	40.68	43.71	46.60	49.20	51.64
15.0	36.91	39.64	42.36	45.08	47.78	50.55
20.0	36.14	38.70	41.26	43.79	46.31	48.99
25.0	35.45	37.86	40.25	42.64	45.01	47.55
30.0	34.83	37.10	39.36	41.61	43.85	46.23
40.0	33.76	35.85	37.95	40.05	42.15	44.38
50.0	32.90	34.78	36.67	38.60	40.53	42.59
60.0	32.19	33.89	35.62	37.37	39.13	41.00
70.0	31.60	33.17	34.75	36.34	37.96	39.67
95.0	30.73	32.13	33.57	35.02	36.48	38.02
125.0	29.83	31.05	32.29	33.57	34.88	36.15

Source: DTN: MO0107MWDTEM05.011

Table VI-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 0.6 kW/m by Additional 30 Years of Aging, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Four)

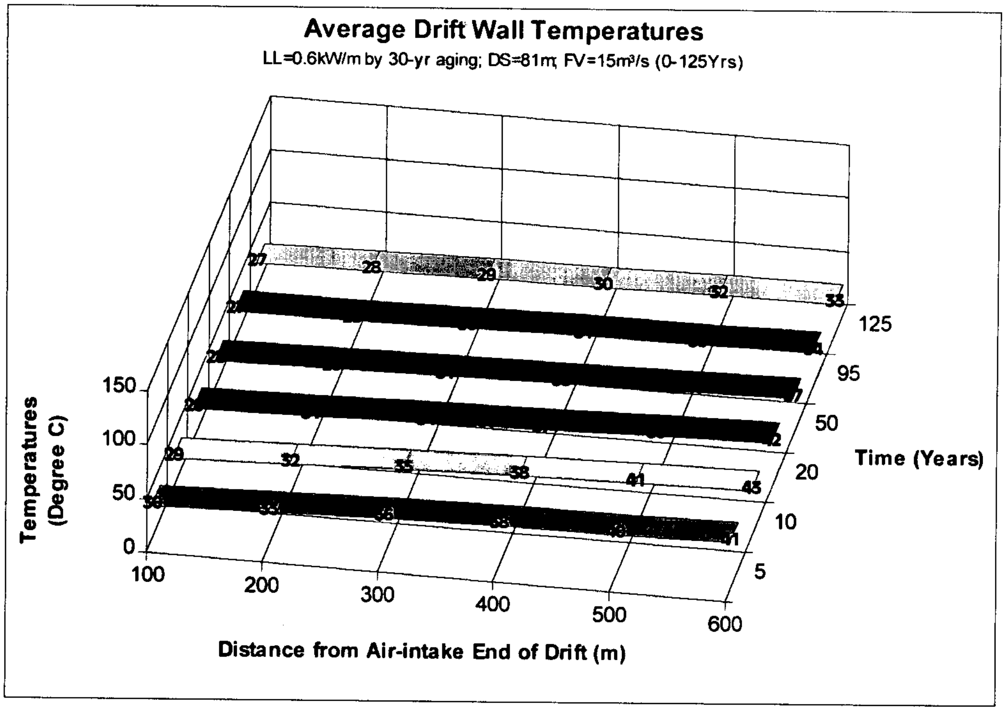
Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.52	66.80	66.80	66.80	66.80	66.80
5.0	54.68	51.52	48.77	46.74	45.24	44.16
10.0	41.70	41.22	39.77	38.07	36.31	34.71
15.0	38.91	38.22	37.50	36.60	35.52	34.31
20.0	36.35	35.73	35.11	34.41	33.68	32.88
25.0	34.02	33.50	32.94	32.32	31.70	31.08
30.0	31.93	31.48	30.98	30.45	29.92	29.38
40.0	29.25	28.90	28.50	28.08	27.63	27.18
50.0	26.19	25.95	25.63	25.34	24.99	24.62
60.0	23.70	23.50	23.25	23.05	22.77	22.48
70.0	21.66	21.50	21.28	21.11	20.89	20.69
95.0	19.36	19.25	19.13	18.97	18.81	18.65
125.0	16.57	16.54	16.51	16.42	16.32	16.22

Source: DTN: MO0107MWDTEM05.011

Table VI-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 0.6 kW/m by Additional 30 Years of Aging, 15 m^3/s (0-125 Years), and 81-m drift spacing (Alternative Scenario Four)

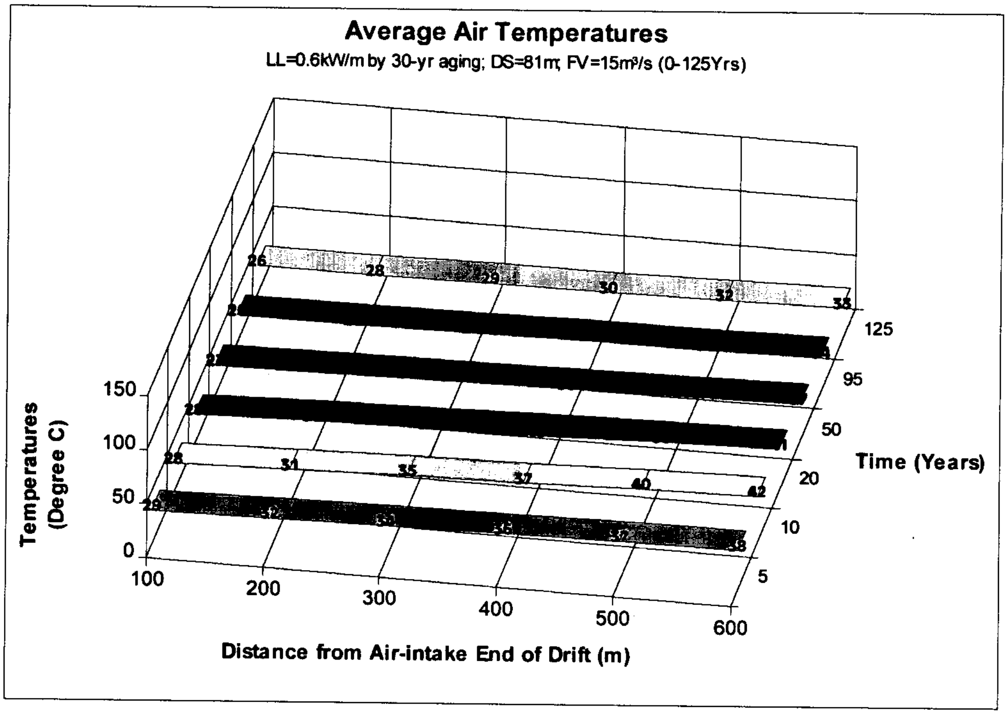
Time (years)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (years)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	55.82%	334.93	334.93	0.00	1.00E-04	400.53	200.26	0.63
5.0	51.65%	309.91	322.42	50839.38	5.0	291.11	345.82	54527.39
10.0	47.95%	287.69	298.80	47114.88	10.0	231.77	261.44	41223.96
15.0	44.63%	267.76	277.72	43791.18	15.0	221.06	226.42	35701.37
20.0	41.66%	249.94	258.85	40815.46	20.0	208.16	214.61	33839.78
25.0	39.01%	234.05	242.00	38157.84	25.0	195.55	201.86	31828.63
30.0	36.62%	219.74	226.89	35776.56	30.0	184.13	189.84	29933.95
40.0	32.56%	195.34	207.54	65450.63	40.0	169.55	176.84	55768.13
50.0	29.26%	175.56	185.45	58483.83	50.0	152.72	161.13	50814.75
60.0	26.57%	159.41	167.48	52817.23	60.0	138.74	145.73	45957.16
70.0	24.38%	146.29	152.85	48202.61	70.0	127.13	132.94	41923.41
95.0	21.09%	126.56	136.42	107557.12	95.0	114.16	120.64	95116.22
125.0	17.49%	104.94	115.75	109507.61	125.0	98.58	106.37	100633.32
Total heat generated in 25 years (GJ)				220718.74	Total heat removed in 25 years (GJ)			197121.76
Total heat generated in 50 years (GJ)				380429.75	Total heat removed in 50 years (GJ)			333638.59
Total heat generated in 125 years (GJ)				698514.33	Total heat removed in 125 years (GJ)			617268.70
Percentage of total heat removal in 25 years = 89%								
Percentage of total heat removal in 50 years = 88%								
Percentage of total heat removal in 125 years = 88%								

Source: DTN: MO0107MWDTEM05.011



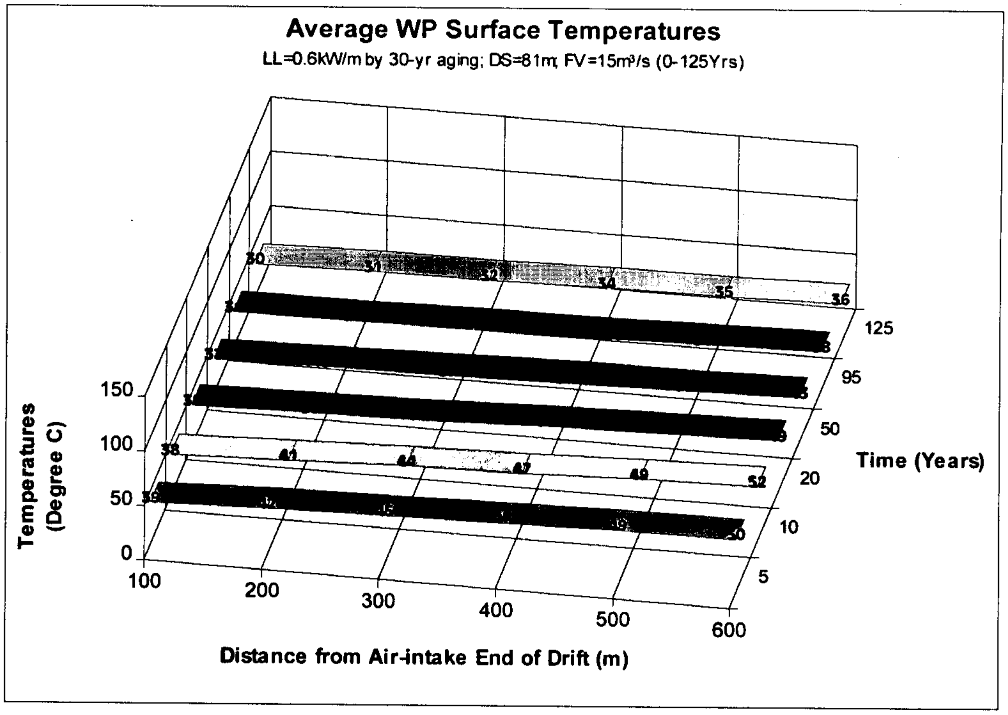
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure VI-1. Average Drift Wall Temperatures for Alternative Scenario Four



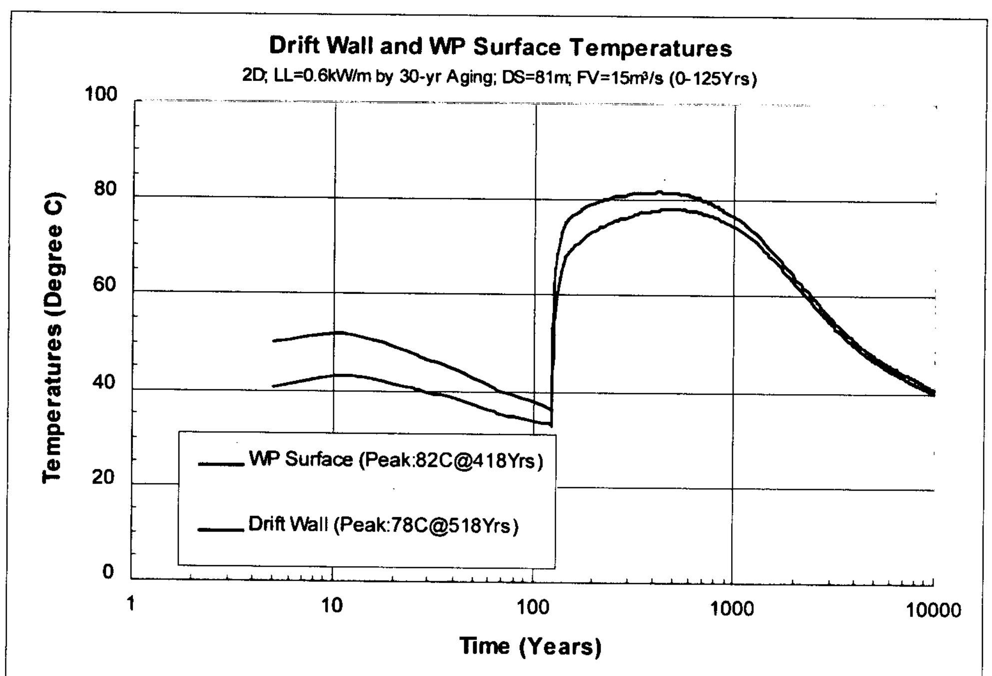
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure VI-2. Average Air Temperatures for Alternative Scenario Four



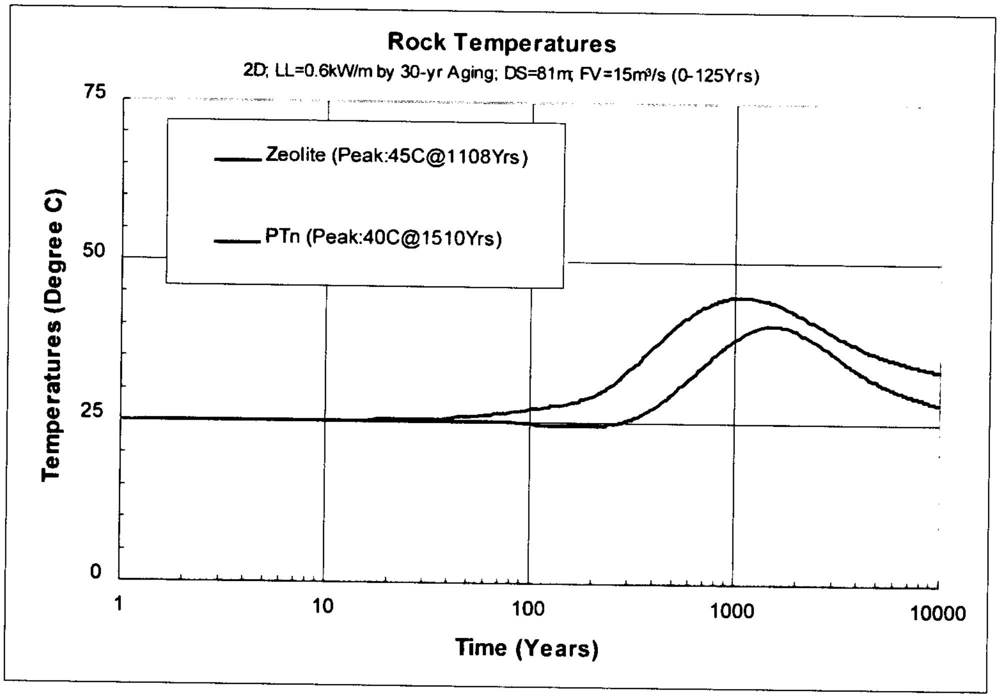
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation

Figure VI-3. Average Waste Package Surface Temperatures for Alternative Scenario Four



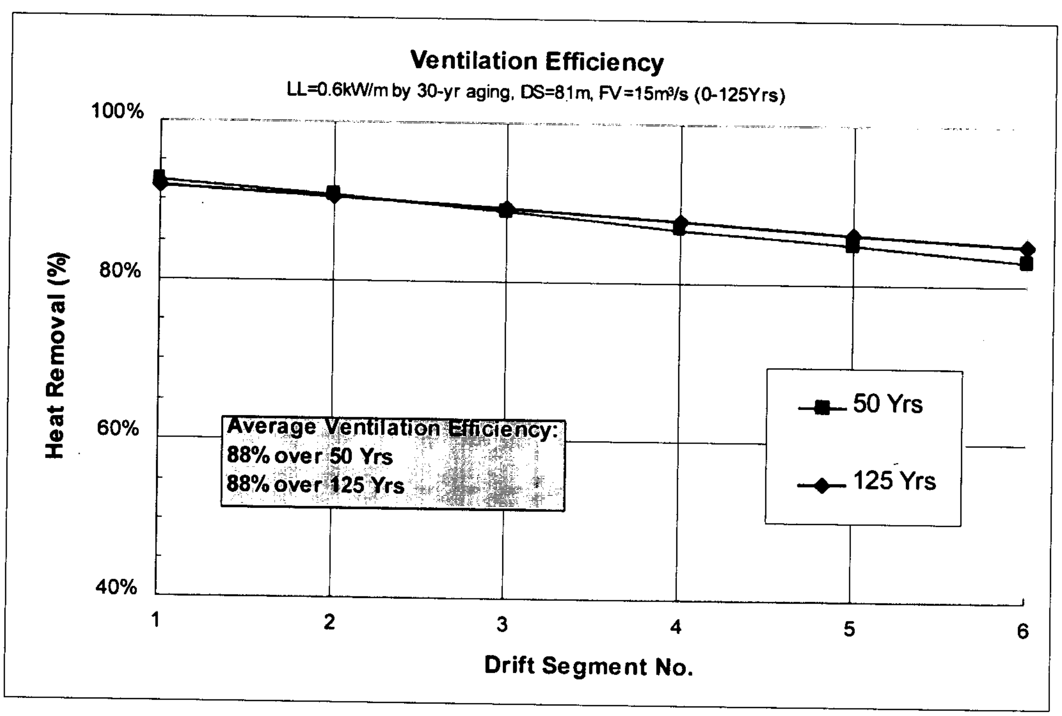
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation (Not to Scale)

Figure VI-4. Drift Wall and WP Surface Temperatures for Alternative Scenario Four



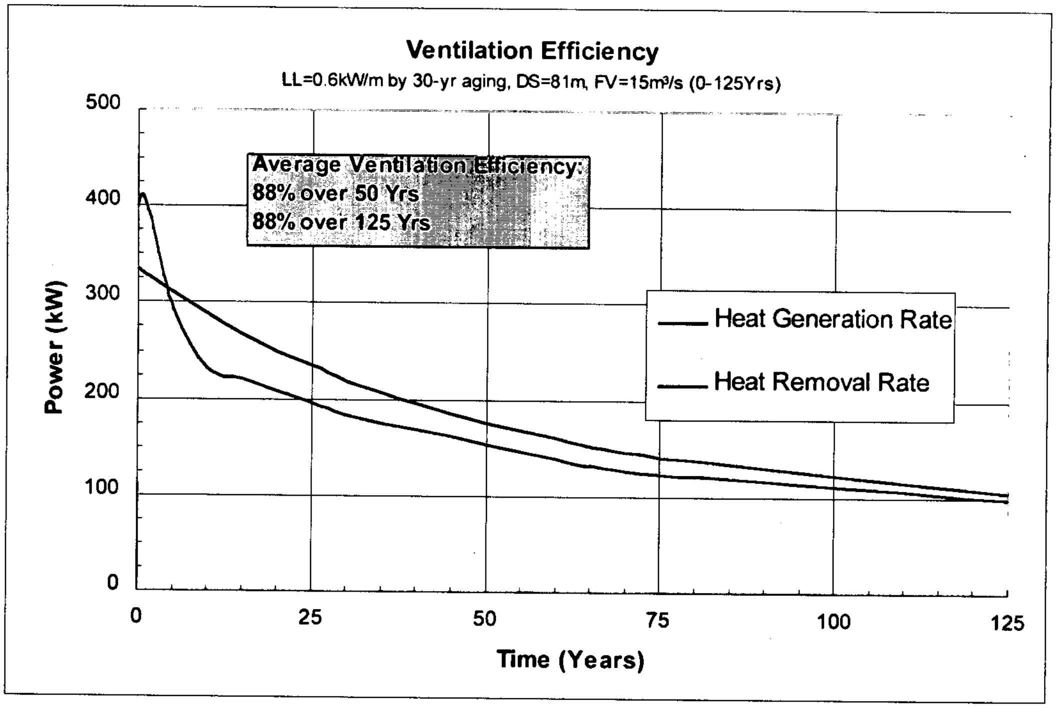
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure VI-5. Rock Temperatures at Zeolite and PTn Unit for Alternative Scenario Four



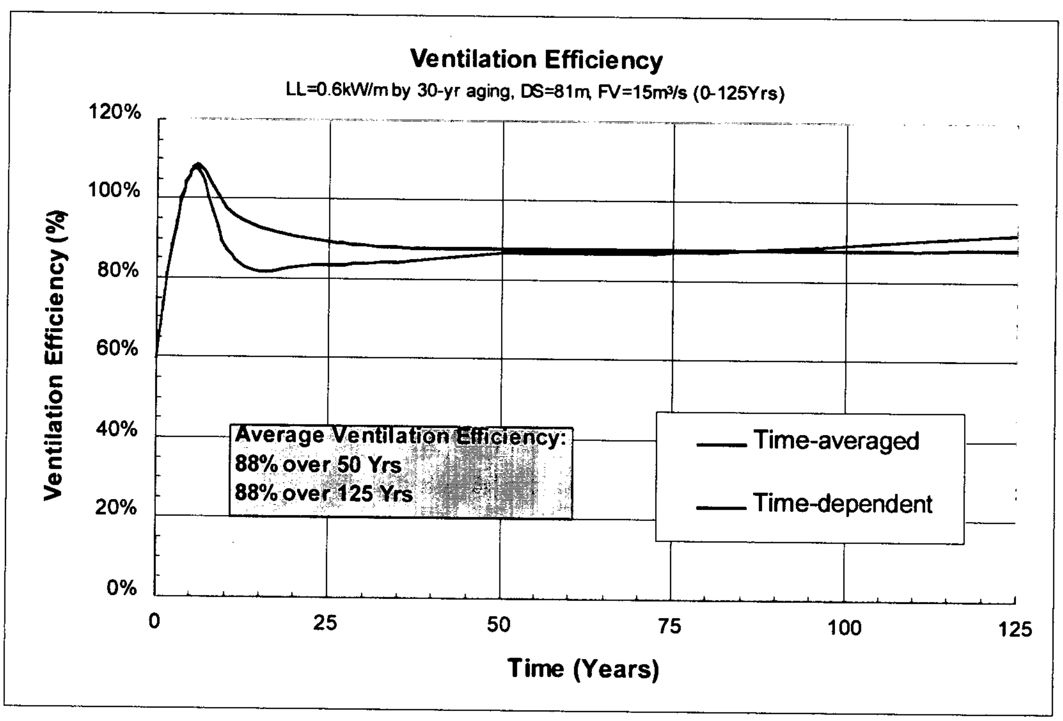
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure VI-6. Average Heat Removal Rates at Different Drift Segments for Alternative Scenario Four



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure VI-7. Overall Heat Generation and Removal Rates at Different Time for Alternative Scenario Four



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation.

Figure VI-8. Time-averaged and Time-dependent Ventilation Efficiencies for Alternative Scenario Four

ATTACHMENT VII

TEMPERATURES AND VENTILATION EFFICIENCY FOR REPRESENTAIVE SCENARIO WITH VARIOUS SEGMENT LENGTHS

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 1.0 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 50 years and natural ventilation air flow rates of 3 m^3/s from 50 to 100 years and 1.5 m^3/s from 100 to 300 years. This case represents *Representative Scenario* of the low temperature repository design, and is analyzed as part of sensitivity of study to examine the effect of varying the segment lengths on results (compared to those presented in Attachment III). All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table VII-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Various Segment Lengths)

Time (Years)	Location Measured from Air-intake End (m)								
	0-25	25-50	50-100	100-150	150-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.84	25.84	25.86	25.86	25.86	25.90	25.90	25.90
1.0	33.47	34.74	35.90	38.08	39.94	41.55	44.39	46.42	47.89
5.0	32.69	34.06	35.42	38.10	40.66	43.09	47.70	51.74	55.17
10.0	31.96	33.22	34.49	37.00	39.50	41.98	46.84	51.51	55.89
15.0	31.37	32.53	33.68	35.99	38.29	40.60	45.18	49.72	54.17
20.0	30.83	31.89	32.96	35.08	37.20	39.32	43.56	47.78	51.99
25.0	30.36	31.34	32.31	34.27	36.23	38.18	42.09	46.01	49.91
30.0	29.95	30.85	31.75	33.56	35.37	37.17	40.79	44.41	48.03
40.0	29.25	30.06	30.86	32.49	34.12	35.76	39.05	42.36	45.69
50.0	28.69	29.39	30.10	31.52	32.95	34.39	37.31	40.28	43.27
60.0	37.99	39.50	40.91	43.57	45.94	48.06	51.95	55.25	58.21
70.0	36.79	38.87	40.84	44.61	48.03	51.12	56.72	61.29	65.09
80.0	35.73	37.67	39.57	43.30	46.84	50.20	56.52	62.03	66.75
90.0	34.84	36.63	38.40	41.88	45.24	48.49	54.74	60.46	65.61
100.0	34.10	35.77	37.41	40.65	43.81	46.87	52.81	58.37	63.52
125.0	38.01	39.99	41.88	45.49	48.81	51.88	57.63	62.70	67.26
150.0	36.41	38.56	40.62	44.58	48.23	51.58	57.78	63.05	67.62
200.0	34.73	36.67	38.57	42.28	45.83	49.17	55.48	61.02	65.84
250.0	33.74	35.47	37.18	40.55	43.81	46.95	52.98	58.47	63.40
300.0	33.00	34.59	36.16	39.27	42.28	45.21	50.87	56.13	60.98

Source: DTN: MO0107MWDTEM05.011

Table VII-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Various Segment Lengths)

Time (Years)	Location Measured from Air-intake End (m)								
	0-25	25-50	50-100	100-150	150-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	26.25	26.25	27.51	27.51	27.51	30.02	30.03	30.03	30.03
1.0	26.37	27.66	30.05	32.11	33.90	36.97	39.23	40.86	42.05
5.0	26.43	27.85	30.65	33.34	35.90	40.75	45.02	48.65	51.68
10.0	26.30	27.61	30.21	32.80	35.37	40.43	45.30	49.88	54.10
15.0	26.19	27.38	29.76	32.13	34.51	39.25	43.95	48.57	53.06
20.0	26.09	27.18	29.36	31.54	33.73	38.09	42.45	46.80	51.11
25.0	26.00	27.00	29.01	31.02	33.02	37.04	41.07	45.09	49.11
30.0	25.92	26.85	28.70	30.55	32.40	36.11	39.83	43.55	47.27
40.0	25.83	26.65	28.31	29.98	31.66	35.03	38.42	41.84	45.26
50.0	25.71	26.43	27.88	29.34	30.81	33.79	36.82	39.88	42.98
60.0	26.73	28.34	31.39	34.08	36.49	40.88	44.58	47.87	50.92
70.0	27.42	29.72	34.12	38.10	41.70	48.21	53.48	57.82	61.48
80.0	27.19	29.35	33.59	37.64	41.49	48.75	55.09	60.52	65.13
90.0	27.00	28.98	32.88	36.66	40.33	47.40	53.90	59.77	64.98
100.0	26.84	28.66	32.26	35.77	39.19	45.83	52.07	57.87	63.21
125.0	27.39	29.66	34.01	37.99	41.67	48.54	54.59	60.04	65.00
150.0	27.58	30.06	34.82	39.19	43.21	50.61	56.87	62.26	66.99
200.0	27.23	29.42	33.72	37.84	41.74	49.11	55.59	61.21	66.10
250.0	26.95	28.87	32.67	36.36	39.93	46.81	53.12	58.80	63.84
300.0	26.76	28.50	31.95	35.30	38.57	44.91	50.85	56.34	61.35

Source: DTN: MO0107MWDTEM05.011

Table VII-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Various Segment Lengths)

Time (Years)	Location Measured from Air-intake End (m)								
	0-25	25-50	50-100	100-150	150-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.86	66.88	66.88	66.90	66.90	66.90	66.93	66.93	66.93
1.0	49.73	50.92	52.02	54.04	55.78	57.30	59.95	61.86	63.24
5.0	47.65	48.92	50.18	52.67	55.06	57.33	61.64	65.42	68.64
10.0	45.55	46.72	47.91	50.25	52.59	54.90	59.47	63.86	67.98
15.0	43.89	44.97	46.05	48.22	50.38	52.54	56.86	61.14	65.35
20.0	42.36	43.36	44.36	46.35	48.35	50.36	54.37	58.37	62.36
25.0	41.01	41.94	42.86	44.72	46.57	48.42	52.13	55.85	59.57
30.0	39.82	40.67	41.54	43.25	44.97	46.69	50.14	53.59	57.05
40.0	37.80	38.58	39.35	40.90	42.47	44.04	47.20	50.37	53.57
50.0	36.17	36.85	37.53	38.90	40.27	41.66	44.48	47.34	50.23
60.0	46.18	47.61	48.95	51.49	53.74	55.77	59.48	62.63	65.45
70.0	44.13	46.13	48.02	51.65	54.94	57.92	63.32	67.73	71.40
80.0	42.39	44.25	46.08	49.67	53.10	56.34	62.46	67.80	72.39
90.0	40.93	42.66	44.37	47.73	50.98	54.13	60.19	65.75	70.76
100.0	39.73	41.34	42.93	46.07	49.13	52.10	57.87	63.28	68.30
125.0	43.07	45.00	46.83	50.35	53.57	56.56	62.15	67.09	71.55
150.0	40.72	42.82	44.84	48.71	52.28	55.56	61.63	66.79	71.27
200.0	38.33	40.23	42.09	45.73	49.21	52.50	58.70	64.15	68.89
250.0	36.92	38.63	40.30	43.61	46.82	49.90	55.84	61.25	66.11
300.0	35.88	37.45	38.99	42.05	45.01	47.90	53.47	58.67	63.44

Source: DTN: MO0107MWDTEM05.011

Table VII-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Various Segment Lengths)

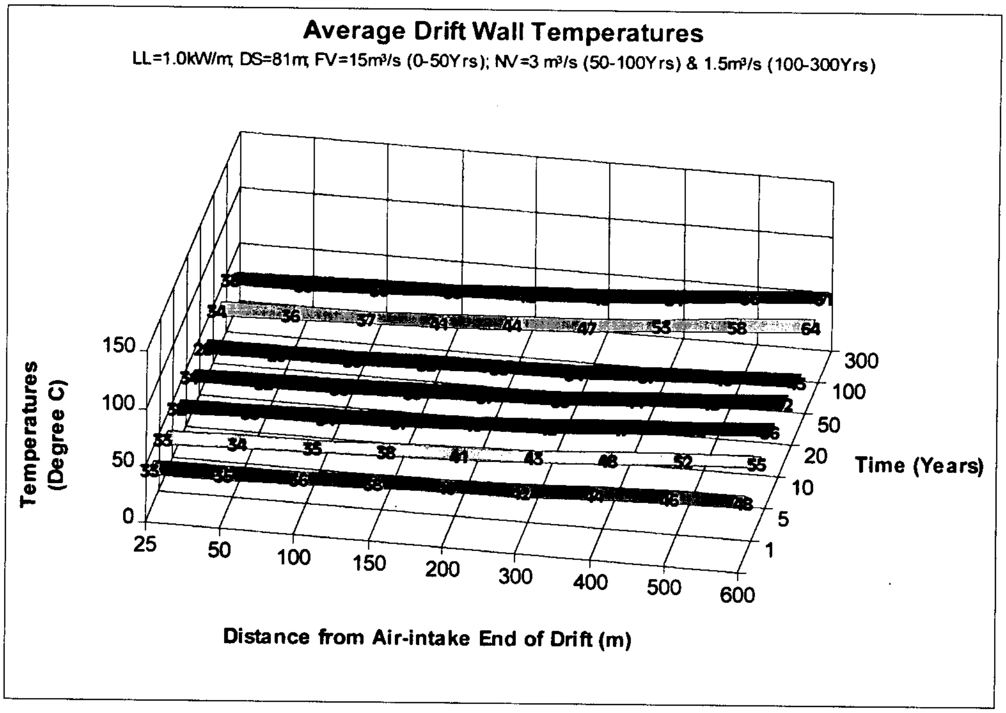
Time (Years)	Location Measured from Air-intake End (m)								
	0-25	25-50	50-100	100-150	150-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	19.11	19.13	36.62	36.66	36.66	66.73	66.87	66.87	66.87
1.0	20.98	20.49	38.43	36.84	35.39	64.29	61.47	59.14	57.43
5.0	21.91	21.70	41.09	40.15	39.11	69.78	66.67	63.58	60.78
10.0	19.92	19.82	37.74	37.31	36.82	65.93	63.90	61.72	59.38
15.0	18.16	18.08	34.47	34.17	33.84	60.81	59.46	57.98	56.34
20.0	16.65	16.59	31.63	31.39	31.12	56.04	54.97	53.86	52.69
25.0	15.30	15.25	29.08	28.88	28.67	51.64	50.76	49.89	48.96
30.0	14.11	14.06	26.83	26.67	26.50	47.72	47.00	46.28	45.48
40.0	12.61	12.59	24.02	23.91	23.78	42.88	42.32	41.71	41.10
50.0	10.92	10.91	20.83	20.78	20.72	37.37	37.01	36.59	36.13
60.0	5.19	5.05	9.28	8.88	8.54	14.92	14.23	13.73	13.31
70.0	7.26	7.05	12.91	12.24	11.62	19.79	18.29	17.13	16.22
80.0	6.59	6.44	11.82	11.27	10.71	17.71	16.00	14.52	13.30
90.0	6.02	5.90	10.87	10.44	9.99	16.55	15.02	13.58	12.28
100.0	5.54	5.44	10.05	9.69	9.32	15.52	14.22	12.96	11.75
125.0	3.56	3.45	6.23	5.88	5.56	9.13	8.25	7.47	6.75
150.0	3.85	3.71	6.68	6.23	5.82	9.36	8.24	7.30	6.50
200.0	3.32	3.23	5.83	5.48	5.13	8.08	7.02	6.11	5.33
250.0	2.90	2.84	5.15	4.90	4.65	7.37	6.49	5.68	4.95
300.0	2.63	2.58	4.70	4.51	4.31	6.92	6.22	5.54	4.89

Source: DTN: MO0107MWDTEM05.011

Table VII-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Various Segment Lengths)

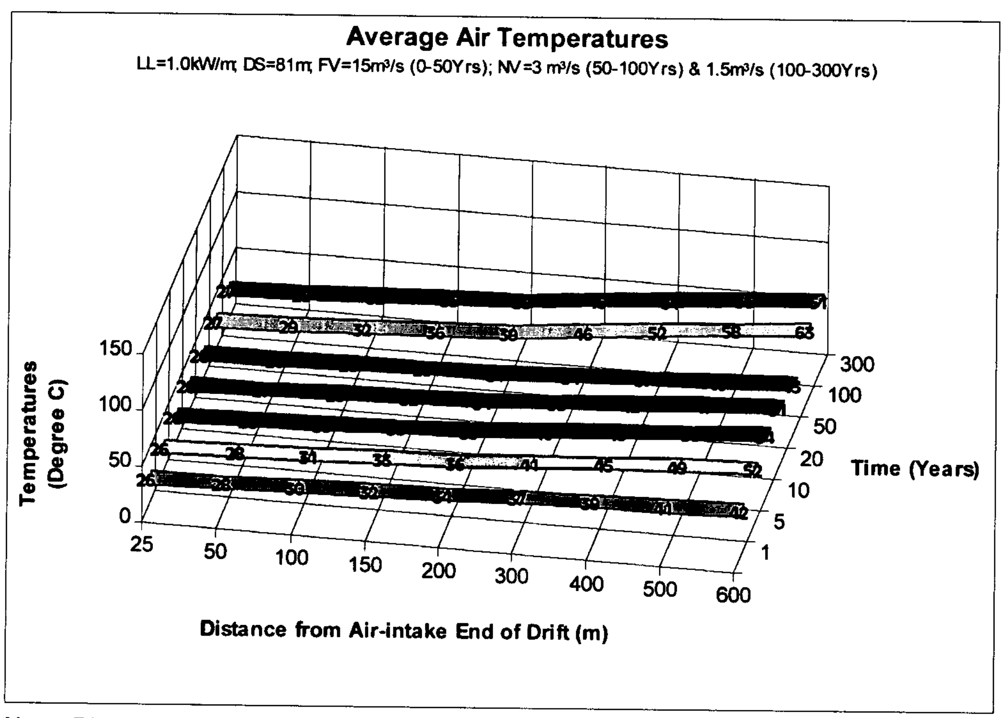
Time (year)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (year)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	600.00	600.00	1.89	1.00E-04	415.54	207.77	0.66
1.0	96.74%	580.44	590.22	18611.27	1.0	394.46	405.00	12770.89
5.0	87.38%	524.29	552.36	69677.23	5.0	424.77	409.62	51670.90
10.0	78.86%	473.18	498.73	78640.52	10.0	402.53	413.65	65224.87
15.0	71.87%	431.22	452.20	71303.13	15.0	373.29	387.91	61166.29
20.0	65.83%	394.97	413.10	65137.23	20.0	344.94	359.12	56625.35
25.0	60.52%	363.09	379.03	59766.08	25.0	318.43	331.68	52299.87
30.0	55.82%	334.93	349.01	55032.19	30.0	294.66	306.54	48335.89
40.0	47.95%	287.69	311.31	98174.34	40.0	264.92	279.79	88234.41
50.0	41.66%	249.94	268.82	84773.91	50.0	231.25	248.09	78236.22
60.0	36.62%	219.74	234.84	74059.91	60.0	93.12	162.19	51146.80
70.0	32.56%	195.34	207.54	65450.63	70.0	122.53	107.82	34003.36
80.0	29.26%	175.56	185.45	58483.83	80.0	108.37	115.45	36407.63
90.0	26.57%	159.41	167.48	52817.23	90.0	100.66	104.51	32958.80
100.0	24.38%	146.29	152.85	48202.61	100.0	94.48	97.57	30769.36
125.0	21.09%	126.56	136.42	107557.12	125.0	56.28	75.38	59431.36
150.0	17.80%	106.82	116.69	91998.85	150.0	57.70	56.99	44930.07
200.0	14.70%	88.22	97.52	153771.16	200.0	49.53	53.61	84538.93
250.0	12.91%	77.49	82.85	130644.56	250.0	44.92	47.23	74469.37
300.0	11.66%	69.95	73.72	116240.31	300.0	42.28	43.60	68751.44
Total heat generated in 25 years (GJ)				363137.36	Total heat removed in 25 years (GJ)			299758.83
Total heat generated in 50 years (GJ)				601117.80	Total heat removed in 50 years (GJ)			514565.35
Total heat generated from 50 to 100 years (GJ)				299014.21	Total heat removed from 50 to 100 years (GJ)			185285.96
Total heat generated from 100 to 300 years (GJ)				600211.99	Total heat removed from 100 to 300 years (GJ)			332121.17
Percentage of total heat removal in 25 years = 83%								
Percentage of total heat removal in 50 years = 86%								
Percentage of total heat removal from 50 to 100 years = 62%								
Percentage of total heat removal from 100 to 300 years = 55%								

Source: DTN: MO0107MWDTEM05.011



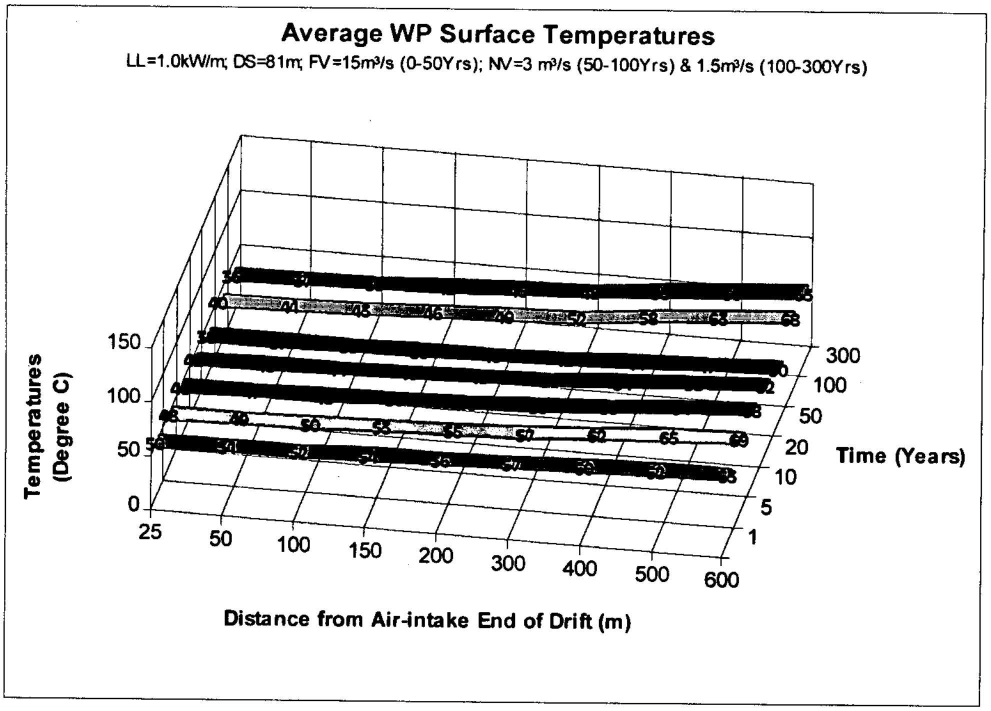
Note: Distance axis not to scale. LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-1. Average Drift Wall Temperatures for Representative Scenario with Various Segment Lengths



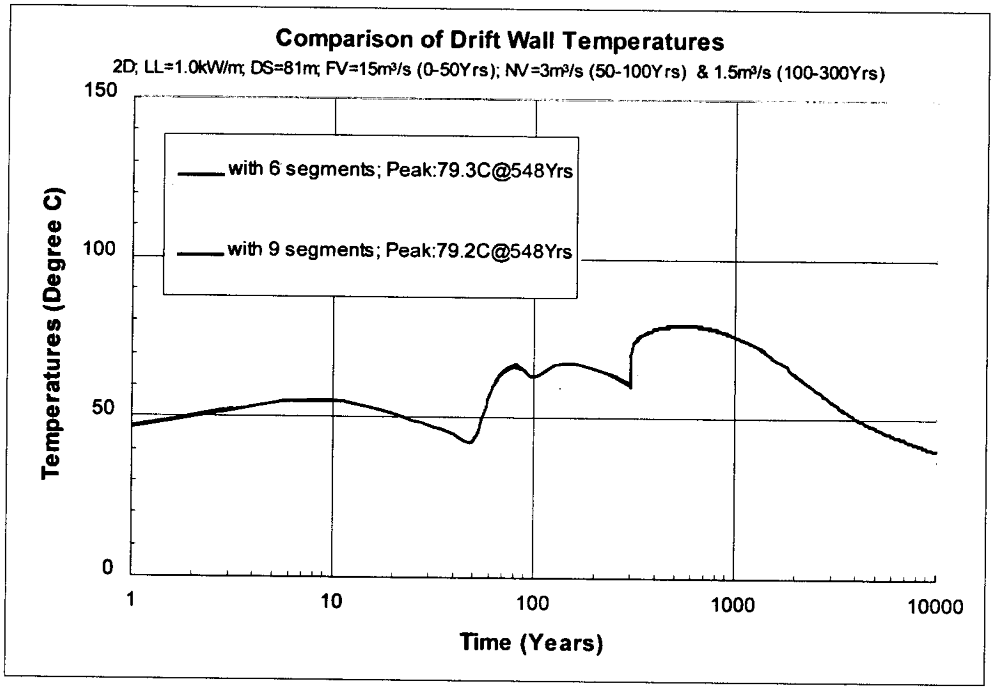
Note: Distance axis not to scale. LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-2. Average Air Temperatures for Representative Scenario with Various Segment Lengths



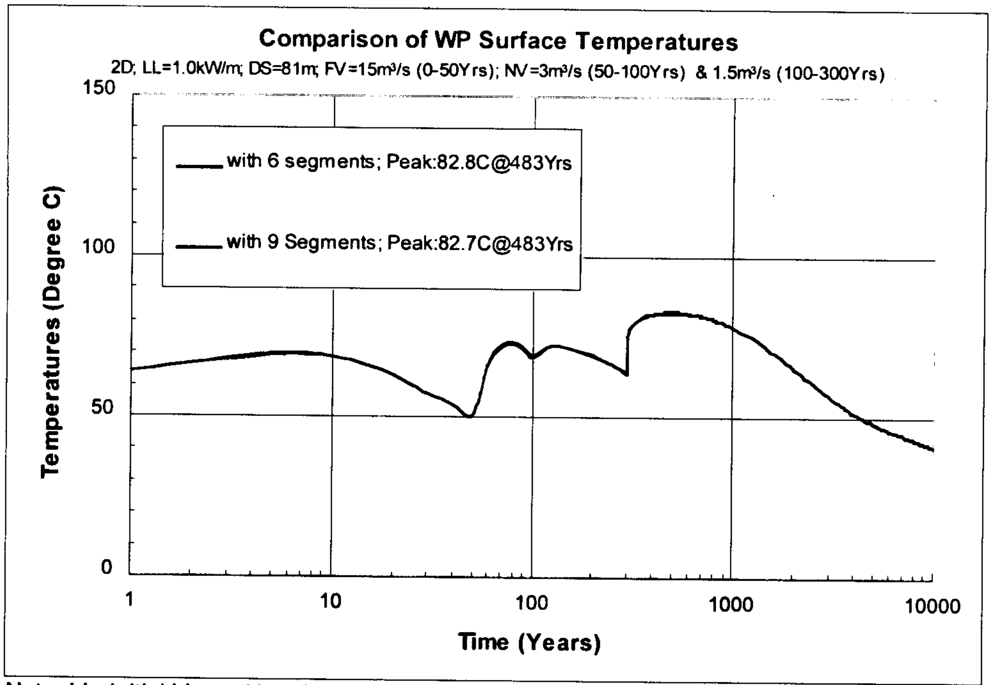
Note: Distance axis not to scale. LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-3. Average Waste Package Surface Temperatures for Representative Scenario with Various Segment Lengths



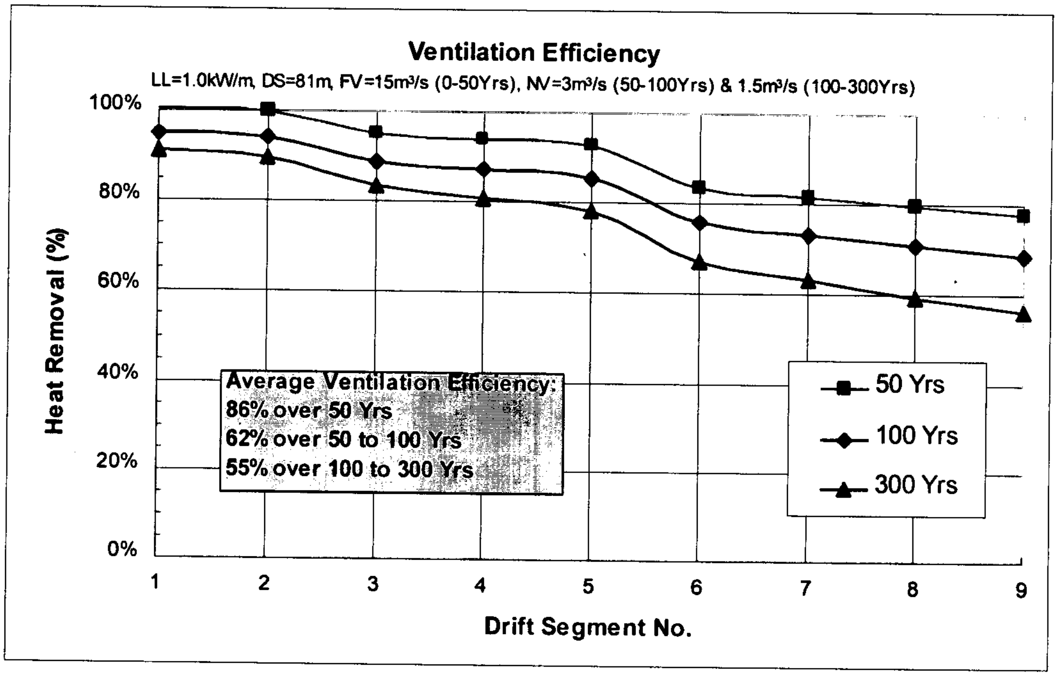
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-4. Comparison of Drift Wall Temperatures for Representative Scenario with Different Segment Numbers



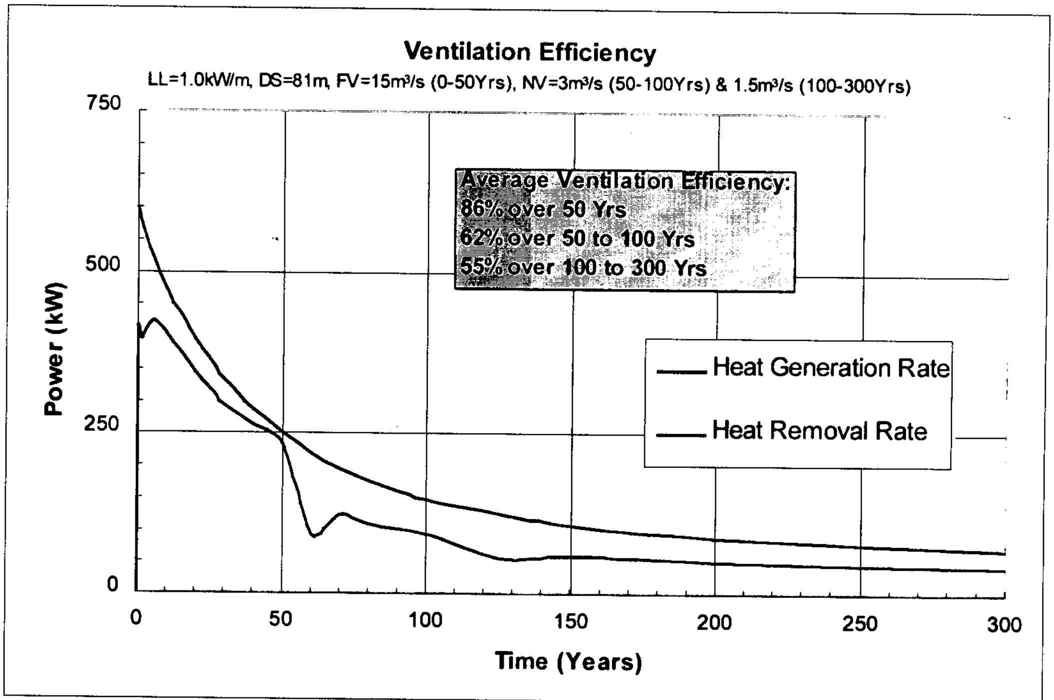
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-5. Comparison of WP Surface Temperatures for Representative Scenario with Different Segment Numbers



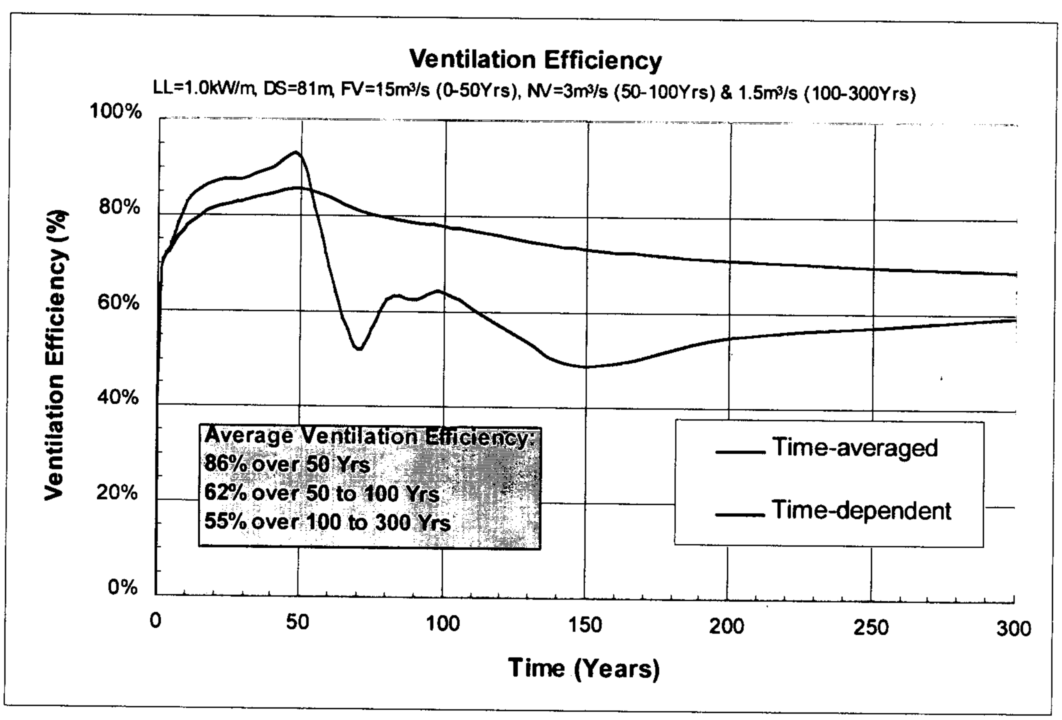
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-6. Average Heat Removal Rates at Different Drift Segments for Representative Scenario with Various Segment Lengths



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-7. Overall Heat Generation and Removal Rates at Different Time for Representative Scenario with Various Segment Lengths



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VII-8. Time-averaged and Time-dependent Ventilation Efficiencies for Representative Scenario with Various Segment Lengths

ATTACHMENT VIII

TEMPERATURES AND VENTILATION EFFICIENCY FOR REPRESENTAIVE SCENARIO WITH HIGHER THERMAL CONDUCTIVITY FOR TPTPLL UNIT

This attachment provides the results of calculations of temperatures and ventilation efficiency (heat removed) for a linear heat load of 1.0 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 50 years and natural ventilation air flow rates of 3 m^3/s from 50 to 100 years and 1.5 m^3/s from 100 to 300 years. This case represents *Representative Scenario* of the low temperature repository design, and is analyzed with higher thermal conductivity for Tptpll unit as part of sensitivity study. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.

Table VIII-1. Average Drift Wall Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Higher Thermal Conductivity for Tptpll Unit)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	25.82	25.90	25.90	25.90	25.90	25.90
1.0	33.42	38.47	42.05	44.63	46.50	47.85
5.0	32.66	38.10	43.25	47.84	51.80	55.12
10.0	31.94	36.94	41.91	46.76	51.40	55.73
15.0	31.35	35.93	40.50	45.03	49.53	53.92
20.0	30.82	35.03	39.23	43.42	47.59	51.74
25.0	30.35	34.23	38.11	41.98	45.84	49.68
30.0	29.94	33.53	37.11	40.70	44.28	47.84
40.0	29.24	32.46	35.71	38.98	42.25	45.54
50.0	28.69	31.49	34.35	37.25	40.18	43.16
60.0	37.80	43.68	48.12	51.71	54.80	57.61
70.0	36.65	44.72	51.26	56.50	60.75	64.26
80.0	35.62	43.20	50.14	56.24	61.48	65.91
90.0	34.76	41.80	48.36	54.42	59.91	64.81
100.0	34.04	40.59	46.76	52.53	57.87	62.79
125.0	37.82	45.54	51.81	57.19	61.95	66.24
150.0	36.29	44.67	51.65	57.45	62.36	66.61
200.0	34.68	42.30	49.23	55.32	60.57	65.07
250.0	33.71	40.58	47.00	52.89	58.20	62.88
300.0	32.99	39.33	45.30	50.86	55.99	60.66

Source: DTN: MO0107MWDTEM05.011

Table VIII-2. Average Air Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Higher Thermal Conductivity for Tptpll Unit)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	25.00	25.00	25.00	25.00	25.00	25.00
1.00E-04	30.01	30.03	30.03	30.03	30.03	30.03
1.0	30.48	34.51	37.41	39.51	41.03	42.13
5.0	30.72	36.16	41.04	45.26	48.81	51.75
10.0	30.20	35.38	40.46	45.33	49.89	54.06
15.0	29.74	34.48	39.19	43.87	48.46	52.91
20.0	29.35	33.69	38.03	42.35	46.66	50.92
25.0	29.00	33.00	36.99	40.98	44.96	48.93
30.0	28.69	32.38	36.07	39.76	43.44	47.12
40.0	28.30	31.63	34.99	38.36	41.75	45.14
50.0	27.86	30.78	33.75	36.76	39.81	42.88
60.0	31.84	36.95	41.03	44.52	47.67	50.63
70.0	34.55	42.30	48.47	53.42	57.47	60.89
80.0	33.69	41.74	48.86	54.97	60.12	64.44
90.0	32.95	40.42	47.36	53.69	59.34	64.29
100.0	32.32	39.25	45.77	51.84	57.45	62.56
125.0	34.45	42.06	48.56	54.31	59.50	64.21
150.0	35.21	43.71	50.72	56.60	61.65	66.07
200.0	33.86	42.02	49.22	55.43	60.74	65.31
250.0	32.76	40.09	46.89	53.05	58.50	63.28
300.0	32.04	38.72	45.00	50.84	56.18	60.99

Source: DTN: MO0107MWDTEM05.011

Table VIII-3. Average WP Surface Temperatures (°C) at Different Time and Locations during Ventilation for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Higher Thermal Conductivity for Tptpll Unit)

Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	70.00	70.00	70.00	70.00	70.00	70.00
1.00E-04	66.86	66.93	66.93	66.93	66.93	66.93
1.0	49.69	54.41	57.78	60.21	61.98	63.25
5.0	47.62	52.69	57.50	61.80	65.52	68.65
10.0	45.53	50.21	54.86	59.42	63.79	67.88
15.0	43.87	48.17	52.47	56.75	60.99	65.15
20.0	42.34	46.32	50.29	54.26	58.21	62.15
25.0	41.00	44.69	48.37	52.04	55.72	59.38
30.0	39.81	43.23	46.65	50.06	53.48	56.89
40.0	37.79	40.88	43.99	47.13	50.28	53.45
50.0	36.17	38.87	41.62	44.42	47.26	50.13
60.0	46.01	51.62	55.86	59.28	62.24	64.92
70.0	44.01	51.78	58.10	63.16	67.25	70.65
80.0	42.29	49.60	56.31	62.23	67.31	71.61
90.0	40.86	47.66	54.02	59.90	65.25	70.02
100.0	39.67	46.02	52.00	57.61	62.82	67.62
125.0	42.89	50.41	56.51	61.75	66.39	70.58
150.0	40.61	48.81	55.65	61.34	66.14	70.31
200.0	38.28	45.76	52.57	58.55	63.72	68.16
250.0	36.90	43.64	49.96	55.76	61.00	65.62
300.0	35.87	42.11	47.98	53.47	58.53	63.14

Source: DTN: MO0107MWDTEM05.011

Table VIII-4. Heat Removed (kW) by Ventilation at Different Time and Locations Based on Combined Spatial and Temporal Correction for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Higher Thermal Conductivity for Tptpll Unit)

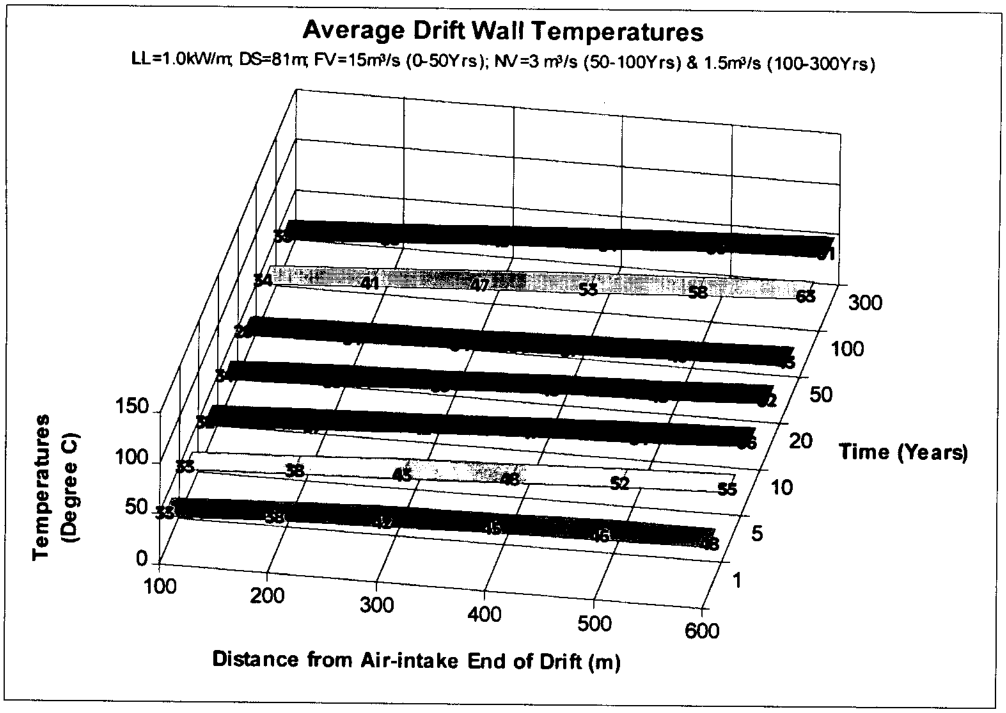
Time (Years)	Location Measured from Air-intake End (m)					
	0-100	100-200	200-300	300-400	400-500	500-600
0.0	0.00	0.00	0.00	0.00	0.00	0.00
1.00E-04	66.60	66.87	66.87	66.87	66.87	66.87
1.0	72.95	67.92	63.64	60.53	58.30	56.69
5.0	76.08	73.09	69.28	65.64	62.37	59.52
10.0	69.22	67.50	65.51	63.27	60.84	58.34
15.0	63.11	61.77	60.42	58.90	57.27	55.49
20.0	57.88	56.78	55.65	54.46	53.24	51.96
25.0	53.20	52.29	51.33	50.35	49.33	48.32
30.0	49.08	48.31	47.50	46.65	45.81	44.93
40.0	43.88	43.33	42.71	42.06	41.37	40.66
50.0	38.01	37.68	37.28	36.84	36.33	35.83
60.0	16.84	15.45	14.53	13.88	13.38	12.98
70.0	23.51	21.03	19.07	17.56	16.42	15.54
80.0	21.38	19.19	17.12	15.30	13.80	12.57
90.0	19.55	17.84	16.13	14.48	12.97	11.62
100.0	18.03	16.60	15.19	13.80	12.46	11.21
125.0	11.15	9.86	8.82	7.94	7.14	6.41
150.0	12.05	10.34	8.95	7.83	6.90	6.11
200.0	10.45	9.07	7.80	6.70	5.78	5.01
250.0	9.15	8.20	7.22	6.29	5.45	4.71
300.0	8.30	7.58	6.84	6.10	5.39	4.72

Source: DTN: MO0107MWDTEM05.011

Table VIII-5. Calculation of Overall Ventilation Efficiency Based on Combined Spatial and Temporal Correction for 600m-long Drift for 1.0 kW/m, 15 m^3/s (0-50 Years), 3 m^3/s (50-100 years), and 1.5 m^3/s (100-300 years) (Representative Scenario with Higher Thermal Conductivity for Tptpll Unit)

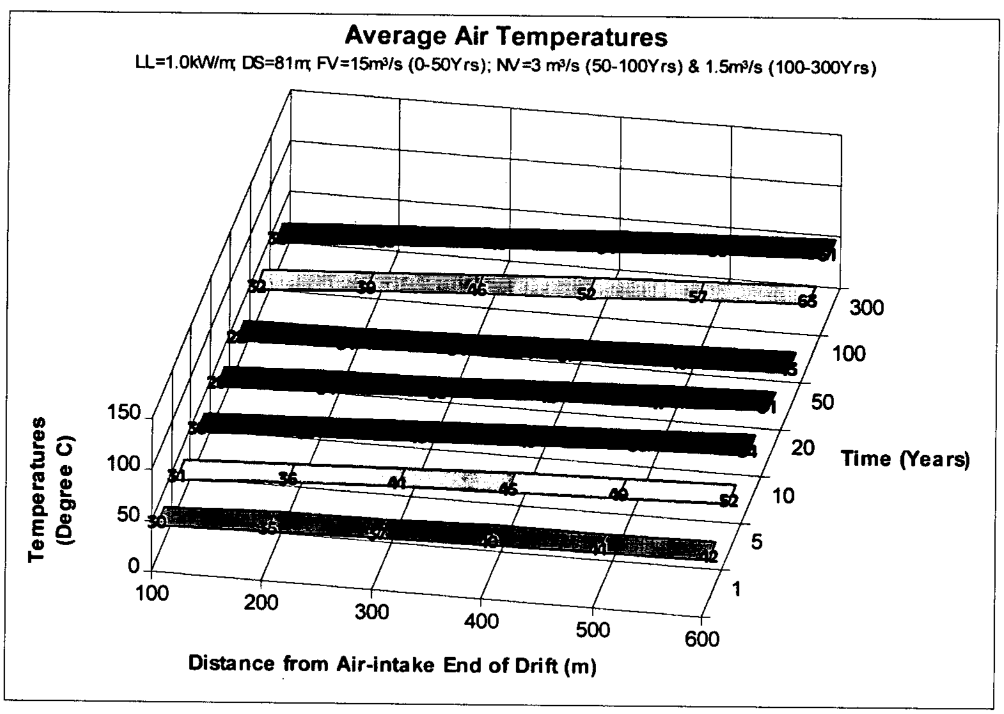
Time (year)	% of Heat Decay	Rate of Heat Generated per 600m (kW)	Average Rate of Heat Generated per 600m (kW)	Heat Generated per 600m (GJ)	Time (year)	Rate of Heat Removed per 600m (kW)	Average Rate of Heat Removed per 600m (kW)	Heat Removed per 600m (GJ)
1.00E-04	100.00%	600.00	600.00	1.89	1.00E-04	400.96	200.48	0.63
1.0	96.74%	580.44	590.22	18611.27	1.0	380.03	390.50	12313.48
5.0	87.38%	524.29	552.36	69677.23	5.0	405.99	393.01	49575.83
10.0	78.86%	473.18	498.73	78640.52	10.0	384.68	395.33	62336.17
15.0	71.87%	431.22	452.20	71303.13	15.0	356.95	370.82	58470.33
20.0	65.83%	394.97	413.10	65137.23	20.0	329.98	343.46	54157.47
25.0	60.52%	363.09	379.03	59766.08	25.0	304.83	317.40	50047.85
30.0	55.82%	334.93	349.01	55032.19	30.0	282.29	293.56	46288.37
40.0	47.95%	287.69	311.31	98174.34	40.0	254.00	268.15	84563.06
50.0	41.66%	249.94	268.82	84773.91	50.0	221.98	237.99	75053.19
60.0	36.62%	219.74	234.84	74059.91	60.0	87.05	154.52	48728.14
70.0	32.56%	195.34	207.54	65450.63	70.0	113.14	100.09	31565.55
80.0	29.26%	175.56	185.45	58483.83	80.0	99.36	106.25	33506.83
90.0	26.57%	159.41	167.48	52817.23	90.0	92.60	95.98	30269.50
100.0	24.38%	146.29	152.85	48202.61	100.0	87.28	89.94	28363.75
125.0	21.09%	126.56	136.42	107557.12	125.0	51.32	69.30	54634.48
150.0	17.80%	106.82	116.69	91998.85	150.0	52.18	51.75	40799.03
200.0	14.70%	88.22	97.52	153771.16	200.0	44.81	48.50	76468.38
250.0	12.91%	77.49	82.85	130644.56	250.0	41.03	42.92	67677.20
300.0	11.66%	69.95	73.72	116240.31	300.0	38.93	39.98	63042.57
Total heat generated in 25 years (GJ)				363137.36	Total heat removed in 25 years (GJ)			286901.78
Total heat generated in 50 years (GJ)				601117.80	Total heat removed in 50 years (GJ)			492806.40
Total heat generated from 50 to 100 years (GJ)				299014.21	Total heat removed from 50 to 100 years (GJ)			172433.77
Total heat generated from 100 to 300 years (GJ)				600211.99	Total heat removed from 100 to 300 years (GJ)			302621.66
Percentage of total heat removal in 25 years = 79%								
Percentage of total heat removal in 50 years = 82%								
Percentage of total heat removal from 50 to 100 years = 58%								
Percentage of total heat removal from 100 to 300 years = 50%								

Source: DTN: MO0107MWDTEM05.011



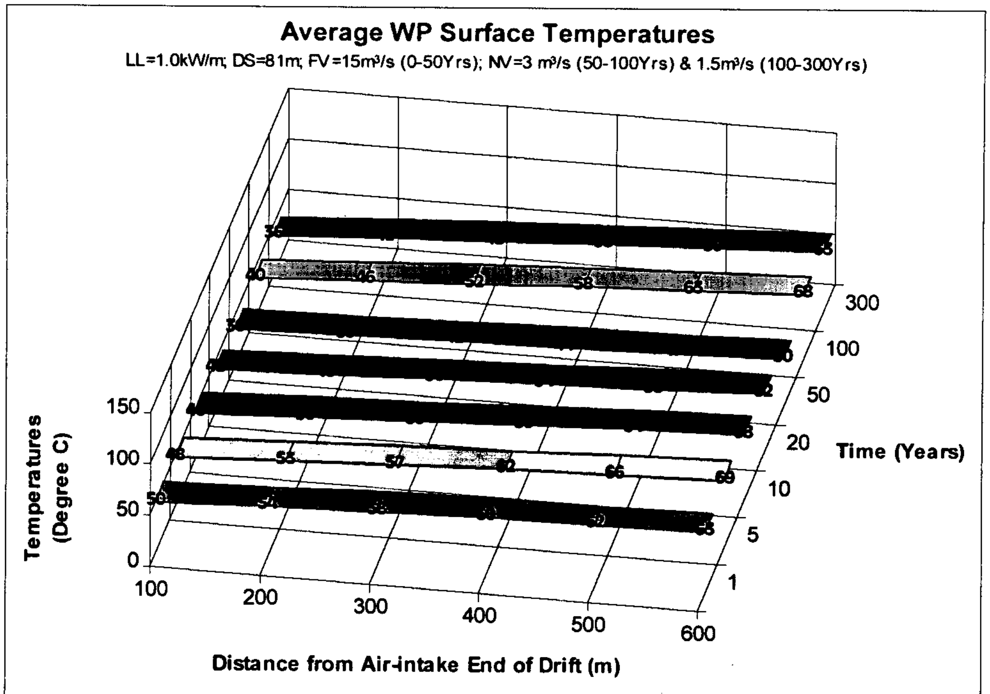
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-1. Average Drift Wall Temperatures for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit



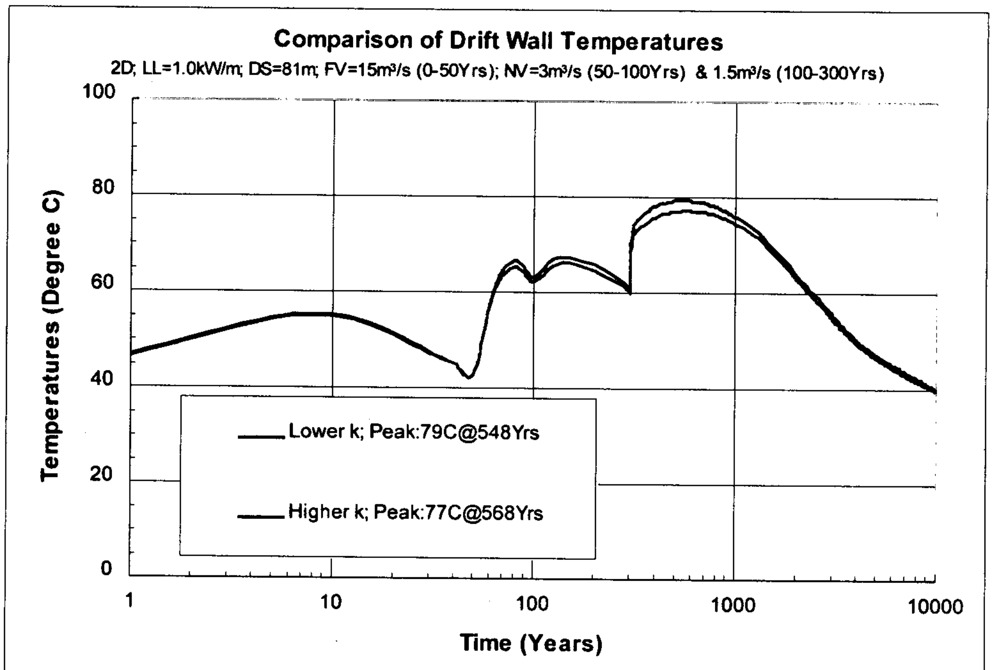
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-2. Average Air Temperatures for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit



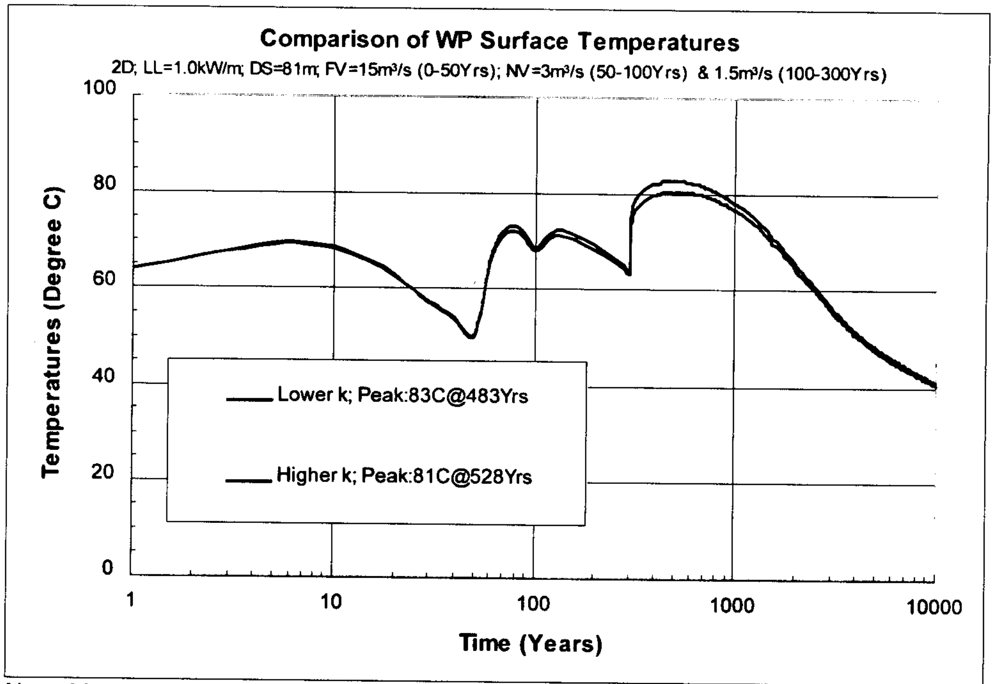
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-3. Average Waste Package Surface Temperatures for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit



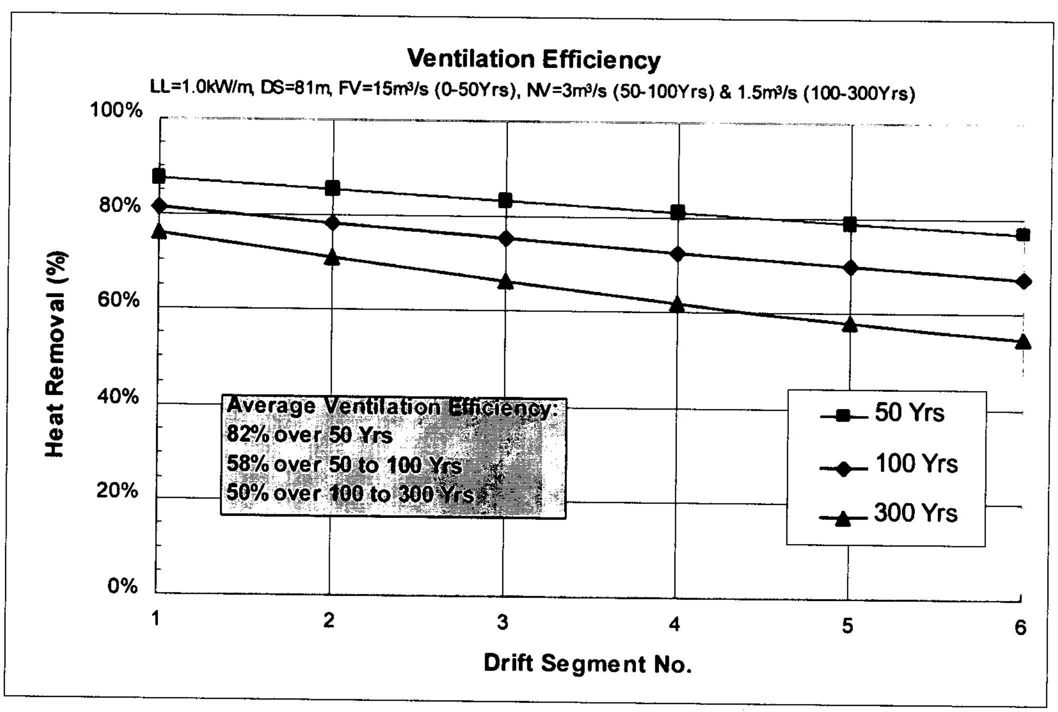
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-4. Comparison of Drift Wall Temperatures for Representative Scenario with Different Thermal Conductivity for Tptpll Unit



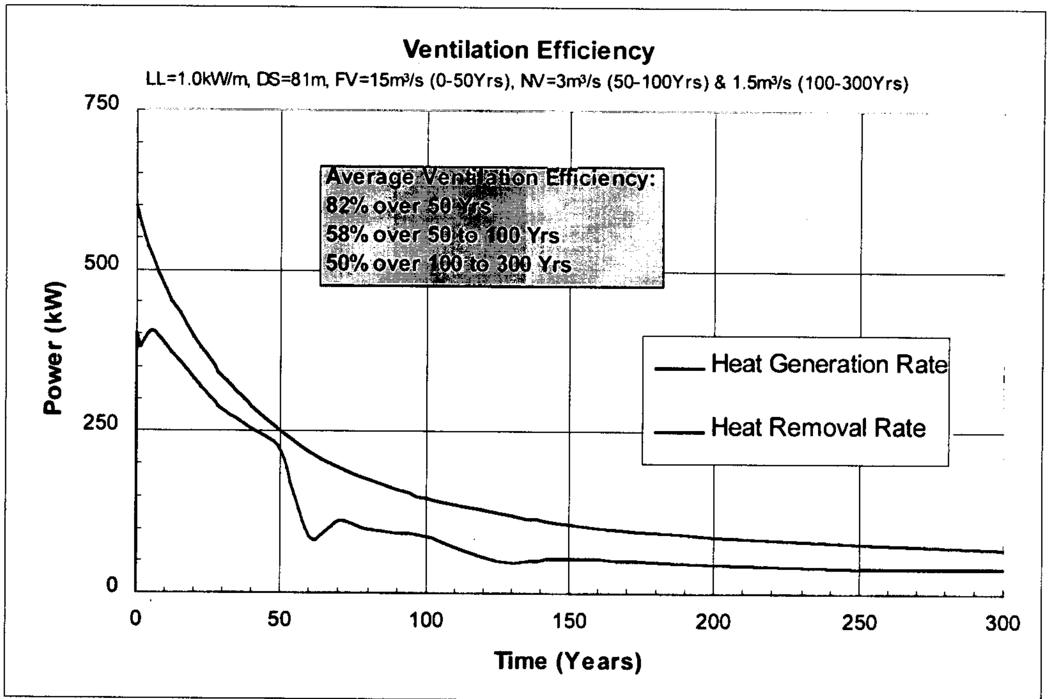
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-5. Comparison of WP Surface Temperatures for Representative Scenario with Different Thermal Conductivity for Tptpll Unit



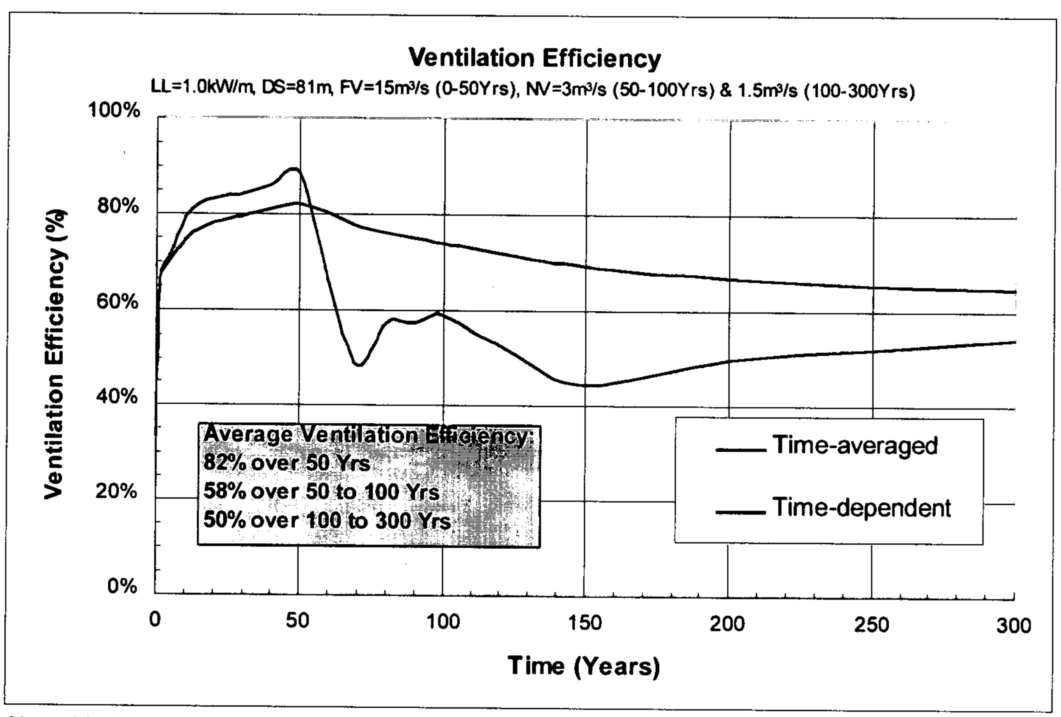
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-6. Average Heat Removal Rates at Different Drift Segments for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-7. Overall Heat Generation and Removal Rates at Different Time for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit



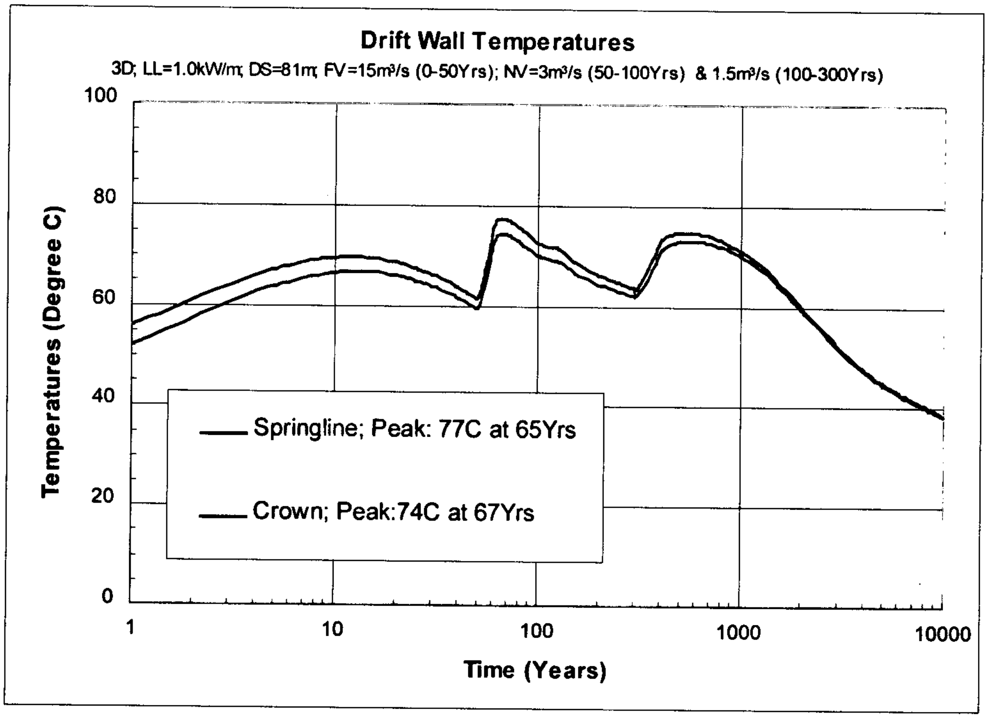
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure VIII-8. Time-averaged and Time-dependent Ventilation Efficiencies for Representative Scenario with Higher Thermal Conductivity for Tptpll Unit

ATTACHMENT IX

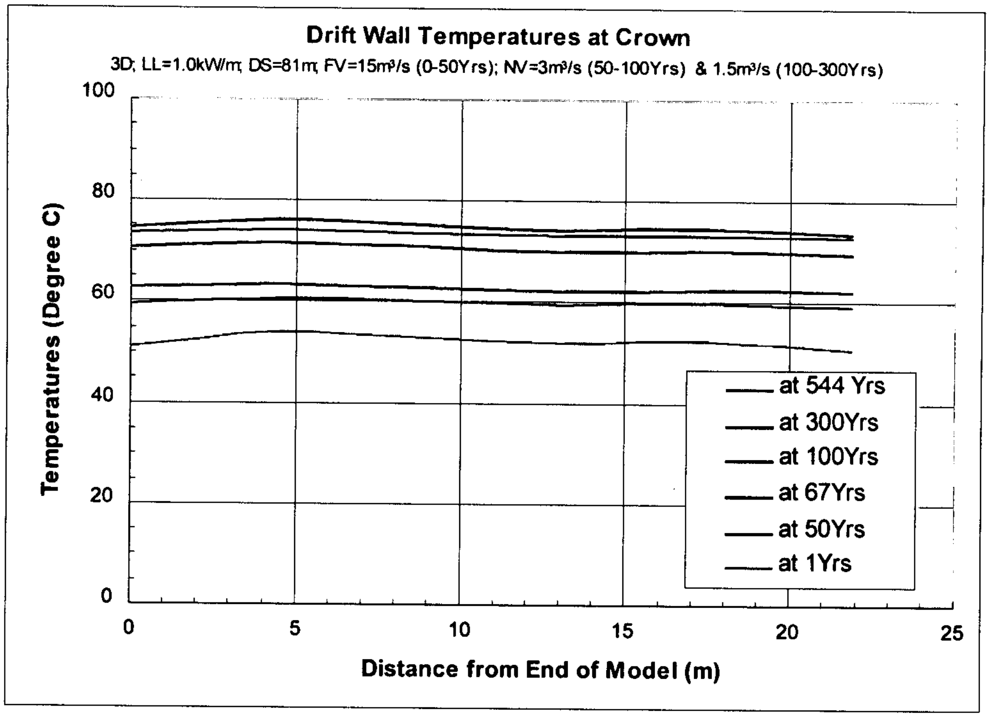
TEMPERATURES OF 3D MODEL FOR REPRESENTAIVE SCENARIO

This attachment provides the results of calculations of temperatures from 3D model for a linear heat load of 1.0 kW/m with a forced ventilation air flow rate of 15 m^3/s from 0 to 50 years and natural ventilation air flow rates of 3 m^3/s from 50 to 100 years and 1.5 m^3/s from 100 to 300 years. This case represents *Representative Scenario* of the low temperature repository design, and is analyzed as part of sensitivity study. As stated in Section 6.3.3.6, ventilation is not explicitly simulated in this 3D model. All data presented in this attachment are obtained from DTN: MO0107MWDTEM05.011.



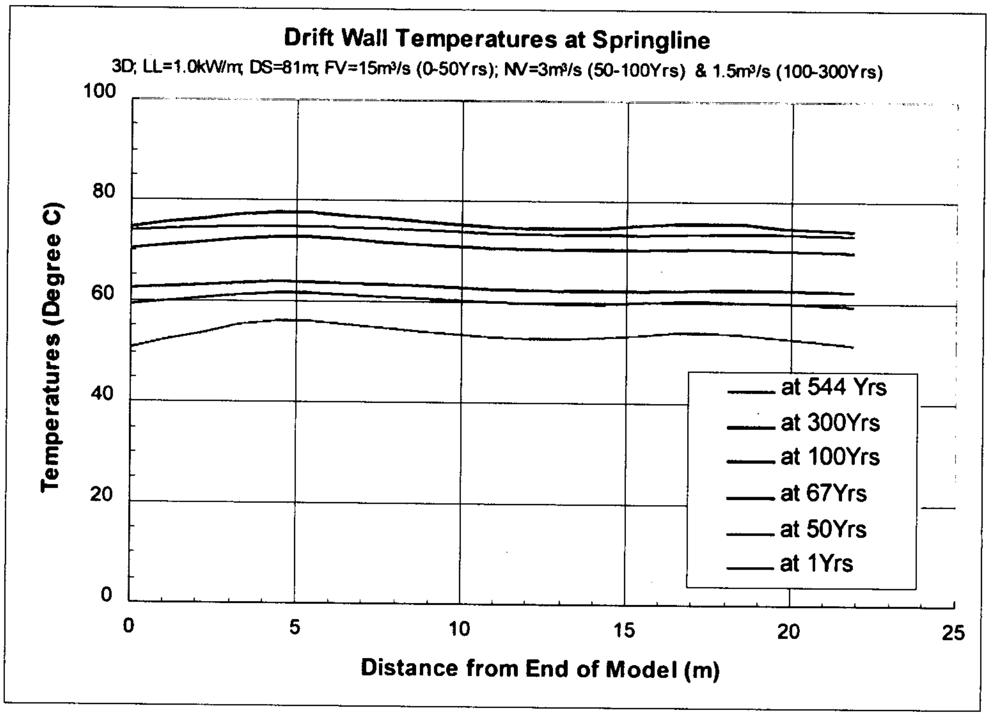
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-1. Drift Wall Temperatures from 3D Model for Representative Scenario



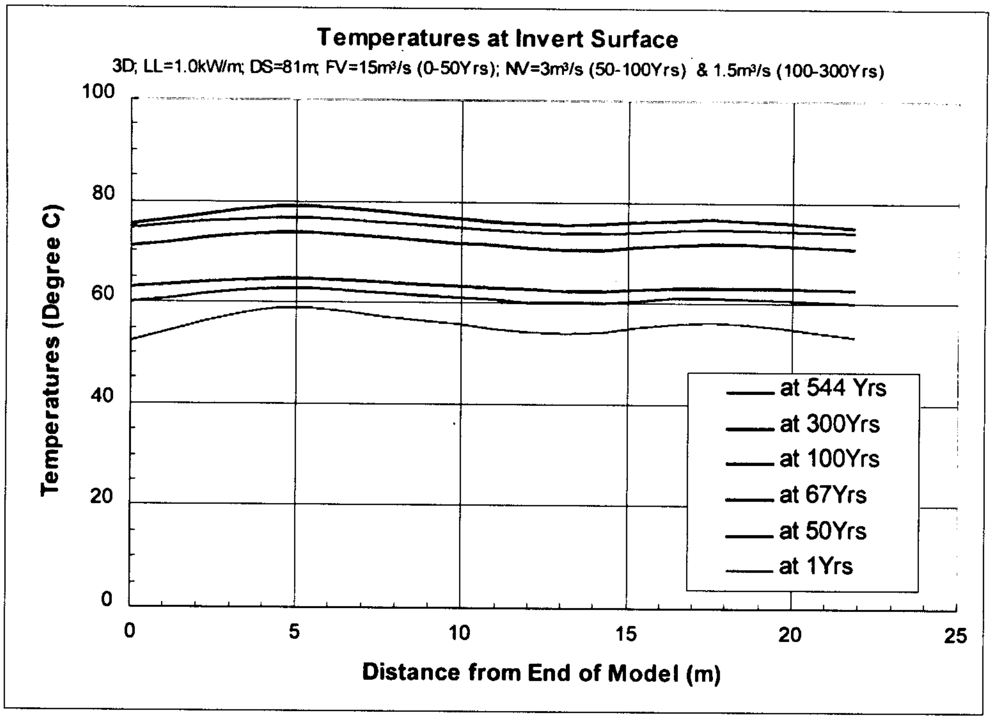
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-2. Drift Wall Temperatures at Crown for Representative Scenario



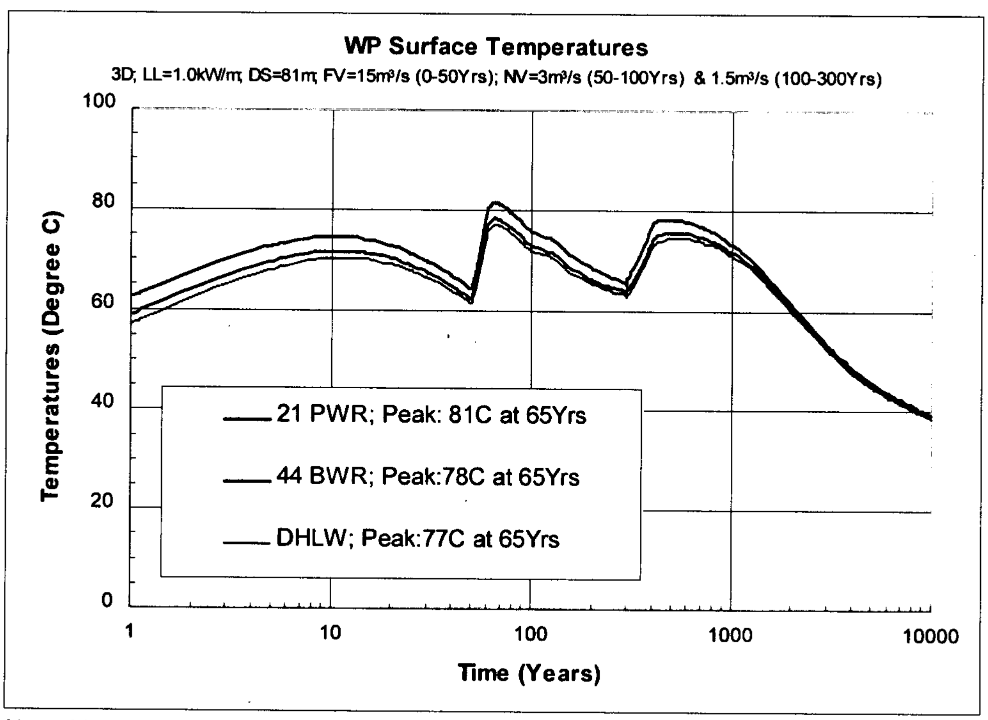
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-3. Drift Wall Temperatures at Springline for Representative Scenario



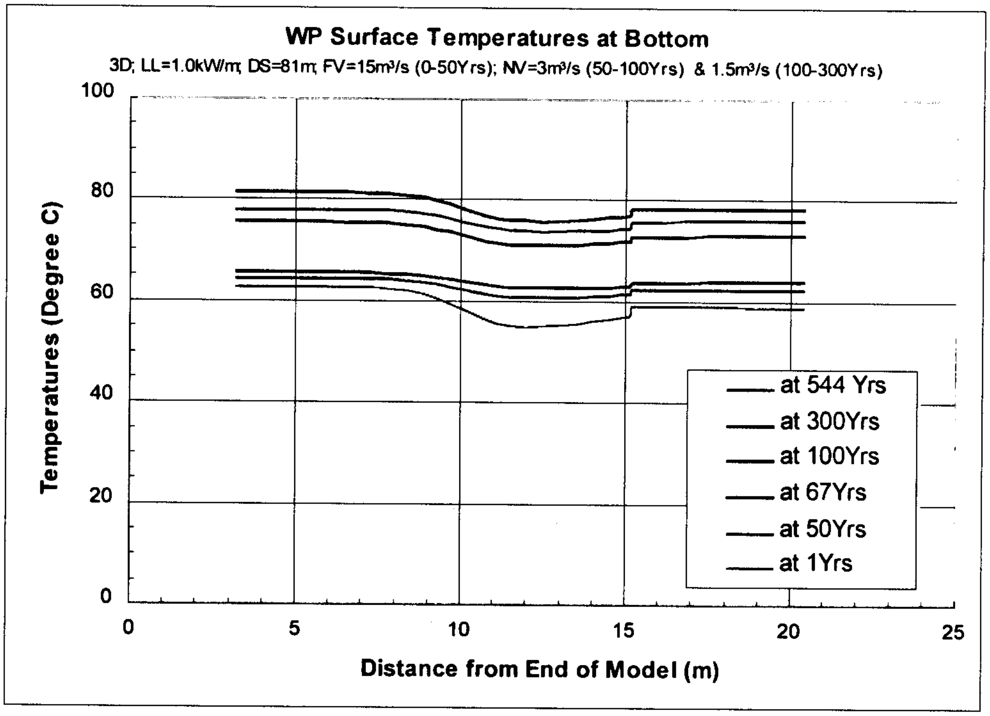
Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-4. Temperatures at Invert Surface for Representative Scenario



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-5. WP Surface Temperatures for Various WPs for Representative Scenario



Note: LL=Initial Linear Heat Load; DS=Drift Spacing; FV=Forced Ventilation; NV=Natural Ventilation.

Figure IX-6. WP Bottom Surface Temperatures for Representative Scenario

ATTACHMENT X

SAMPLE CALCUALTIONS FOR CONVECTION HEAT TRANSFER COEFFICIENT

Sample calculations for Convection Heat Transfer Coefficient for an air flow rate of 1.5 m^3/sec used in Section 6.2.3.3, Table 6-3 are shown as follows:

Given:	Emplacement Drift diameter is 5.5 meters	(Section 4.2.5)
	Emplacement Drift Invert maximum depth is 0.806 meters	(Section 5.9.2)
	21-PWR Waste Package diameter is 1.564 meters	(Section 5.8.4, Table 5-7)
	Air density is 1.0561 kg/m^3	(Section 5.9.5)
	Air dynamic viscosity is 1.8363×10^{-5} kg/ m·s	(Section 4.1.2, Table 4-1)
	Air Prandtl Number is 0.709	(Section 4.1.2, Table 4-1)
	Air Thermal Conductivity is 0.0261 W/m·K	(Section 4.1.2, Table 4-1)

Geometry: Emplacement drift is considered to contain a sector (pie shape) with radius 2.75 meters. The sector contains a triangle with hypotenuse 2.75 meters and altitude 1.944 meters. (2.75 - 0.806). The base of this triangle is formed by the invert.

Contained angle:

$\cos \alpha = 1.944/2.75$ $\qquad \alpha = 45.016\,°$

Since this represents one half of the contained angle, twice $\alpha = 90.032\,°$

Segment arc length:

$Al = r\alpha\pi/180$ $\qquad Al = 4.32$ m

Area of the sector:

$As = r\,Al\,/\,2$ $\qquad As = 5.94\ m^2$

Area of the contained triangle:

$base = r \sin \alpha$ $\qquad base = 1.945$ m

Since this represents one half of the triangle, the *base* = 3.89 m for the whole triangle.

Area of the triangle = 3.89(1.945)/2 $\qquad$ 3.78 m^2

Area of the Invert: (Sector - contained triangle) $\qquad$ 2.16 m^2

Area of the 21-PWR: $\qquad A = \pi r^2$ $\qquad$ 1.92 m^2

Area of the emplacement drift: $\qquad$ 23.76 m^2

Therefore, Area in Flow is,

$$23.76 - 1.92 - 2.16 = 19.68\ m^2$$

(Calculation continued on p. X-3)

Calculation of the wetted perimeter

Circumference (πD) of emplacement drift and 21-PWR are 17.28 and 4.913 meters, respectively.

17.28 - 4.32 + 3.89 + 4.913 = 21.76 m

Hydraulic diameter (Eq. 6-13) = 4(19.68)/21.76 = 3.62 m

Air Flow Velocity = 1.5 m^3/sec ÷ 19.68 m^2 = .07622 m/s

Reynolds Number (Eq. 6-12) = 1.0561 kg/m^3 (.07622 m/s) (3.62 m) ÷ 1.8363×10^{-5} kg/m · s
= 15869

Nusselt Number (Eq. 6-14) = $0.02\ (15869^{0.8})\ .709^{1/3}\ (5.5/1.564)^{0.53}$
= 79.64

Convection Heat Transfer Coefficient (Eq. 6-15) = 0.0261 W/m·K (79.64) ÷ 3.62 m

= 0.57 W/m^2·K